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MONTEREY, CALIFORNIA

THESIS

OPTIMIZING OPERATIONAL AND LOGISTICAL PLANNING IN A THEATER OF OPERATIONS

by

Frank Hallmann

June 2009

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The United States Navy (USN) as well as other allied naval forces deploy their ships worldwide to support and conduct various maritime missions ranging from humanitarian aid to combat. In order to accomplish these missions and maintain a sustained deployment it is paramount to establish a robust means of logistic support. We present two operational planning tools to respectively plan Combat Logistics Force shuttle ship schedules to simultaneously support all U.S. Navy operating ships worldwide, and a Navy Mission Planner with new logistics features to decide where combatants should locate to perform their missions in a particular area of operations, and how to arrange logistics support of these combatants. These operational decision aids use optimization to suggest alternate courses of action for operational and logistics planners to consider. We discuss how the former model has been used by U.S. 2nd Fleet in their exercise Trident Warrior 09. We additionally present a face valid scenario for the Navy Mission planner showing different planning results when logistics are incorporated into the planning process.

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OPTIMIZING OPERATIONAL AND LOGISTICAL PLANNING IN A THEATER OF OPERATIONS

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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June 2009

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Air Defense
ASW	Anti Submarine Warfare
AOO	Area of Operations
BBLS	Barrels
BG	Battle Group
CG	Cruiser, guided missile
CLF	Combat Logistic Force
CMC	Combined mission capability set
CONOPS	Concept of Operations
COA	Course of Action
CVN	Aircraft Carrier, nuclear
DFM	Distilled Fuel Marine (NATO F75/76)
DDG	Destroyer, guided missile
FFG	Frigate, guided missile
GAMS	General Algebraic Modeling Language
INTEL	Intelligence
ISR	Intelligence, Surveillance, and Reconnaissance
JP5	Aviation Fuel (NATO F44)
MCM	Mine Counter Measures
MIO	Maritime Interdiction Operation
MOC	Maritime Operations Center
NMCI	Navy Marine Corps Internet
NMP	Navy Mission Planner
STNS	Short tons
STRIKE	Strike (Attack) Mission
SUW	Anti Surface Warfare
T-AFS	Combat stores ship
T-AE	Ammunition ship
T-AKE	Modular dry cargo and ammunition ship
T-AO	Fleet replenishment Oiler
T-AOE	Fast Combat Support Ship
USN	United States Navy

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EXECUTIVE SUMMARY

Maritime operational planning must synchronize various threads and combine them into an integrated operating plan. The maritime force commander and his planning staff have to devote a large amount of time to evaluate all these different threads in parallel and organize them prior to employing resources into theater. Usually, the planning staff uses un-automated processes to keep track of the various input factors ranging from the simple organization of the area of operations into different regions to synchronized time-phased allocation of forces to accomplish various missions over the entire spectrum.

We present two decision aids, the Combat Logistic Force (CLF) planner and the Navy Mission Planner (NMP), that use integer linear programming to support the planning staff and yield provable, mathematically optimal results. Both presented models use different approaches to solve the given problems.

The CLF planner was originally a strategic planning tool seeking optimal deployment schedules to support combat operations based on multiple battle groups (BG) worldwide. It uses integer linear programming to evaluate where and when supply ships may be prepositioned in order to replenish BGs en route. Thereby, it uses a given operational plan represented by exogenous BG navigational tracks. We add enhanced features to the decision aid enabling operational planning. The CLF planner is implemented in a Microsoft Excel graphical user interface that provides access to all important features such as an animation feature, a saw-tooth diagram, and a collection of maps visualizing common operating areas.

NMP originally was a purely operational decision aid that uses constrained enumeration to generate near-optimal employment schedules for surface combat ships to accomplish required missions in a confined area of operations. We add the possibility to also evaluate employment schedules for logistic ships supporting the combat ships. The decision aid is implemented in an Excel

spreadsheet that uses Visual Basic to enumerate candidate employment schedules for both combat ships and supply ships. The new logistics feature includes a saw-tooth diagram to illustrate the daily inventory of the four main commodity groups for each individual ship. Furthermore, we include the capability to enable escort and close escort missions.

CLF and NMP are very flexible and can support almost any scenario, and produce feasible and provably optimal solutions to scheduling problems. Both decision aids expedite the evaluation of possible courses of action, and produce better results than manual planning. The enhanced CLF planner is currently under evaluation by U.S. 2nd Fleet and NWDC in the command and control exercise Trident Warrior 2009.

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I. INTRODUCTION

A. OVERVIEW

The United States Navy (USN) as well as other naval forces deploy their ships all around the globe to conduct and support various maritime missions ranging from humanitarian aid to combat. In order to accomplish these missions and maintain a sustained presence within an area of operations (AOO), it is paramount to establish a robust means of logistic support.

A logistic network can take several forms and can function in several ways. Support for individual ships in smaller scenarios may be established by using civilian port facilities for direct support such as refueling, disposing, and restocking with perishable goods, as well as all other means of transportation in order to supply units with urgent needs wherever they make berth. However, this might only be a suitable solution when we do not face possible hostilities within the designated operating area.

If a maritime mission is conducted to enforce political will, e.g., a United Nations Security Council Resolution, it might become necessary to establish the logistic network by purely military means. In order to achieve the highest level of sustainment for current operations, it is mandatory to find the right mix of logistic station ships, and shuttle ships. Station ships are referred to as supply vessels that are directly assigned to accompany, e.g., a Carrier Battle Group, and shuttle vessels are referred to as units that roam the area of operations and replenish individually operating units. Civilian facilities may still have to be used. Furthermore, these civilian facilities may also be embellished to full-scale Forward Logistic Sites, and thereby gain an even higher importance for intra-theater logistic operations.

However, due to the inherent nature of maritime operations, time and distance constraints within the theater of operations are of prime importance. In order to assure adequate logistic support, the operational and the logistic

planners need to take into account which strategy to apply. For instance, we might preposition supply units at stationary geographic points within the AOO, and expect combatant ships to meet us there for resupply, or we might schedule supply units to transit through the AOO to supply surface combatants whenever necessary based on a, for example, 14–30 day recurring schedule.

B. PROBLEM DEFINITION

Whenever speaking about military mission planning, especially maritime mission planning, logistics are of paramount importance in order to sustain any operation. Unfortunately, because the maritime environment imposes constraints, such as slow speeds, larger AOO, and longer distances to cover between combatants and supply units, the availability of supply ships within the AOO can impose a constraint on the versatility of preplanned missions necessary to accomplish the overall mission objective. Logistic support in a potentially hostile environment needs to be preplanned to ensure necessary support.

It is important to determine whether the availability of logistic units imposes a constraint on operational mission planning, or if the logistic mission needs to adapt and be planned so as to meet all requirements to ensure complete fulfillment of the operational goal. Therefore, the military combatant commander and his planning staff need to address this issue from the earliest planning stages and review the plan continuously during planning. Operational planning and logistic planning cannot be regarded as two independent processes.

In order to execute such intertwined mission planning it is necessary that both operational and logistic planners understand the planning objectives of one another. Having determined which operational and logistic strategy is to be applied, the planning needs to be continuously adjusted to fulfill the mission objectives necessary for overall mission success (Eccles, 1959, p. 68 pp).

C. OBJECTIVES

In order to provide combatant commanders a reliable decision aid, this thesis develops a tool that determines feasible deployment schedules for Combat Logistic Force (CLF) units to fulfill logistic requirements, without restricting the operational plan. We modify the Navy Mission Planner (NMP) (Dugan, 2007) which was developed as a decision support tool to provide an optimal deployment schedule for surface combatants given a defined mission set in a confined AOO, and integrate functionalities based on the CLF planning tool (Brown and Carlyle, 2008), which provides optimal deployment schedules for CLF units, into the NMP, creating an enhanced automated operational and logistic planning tool.

The output of the operational planning tool includes optimal scheduling of surface combatants given the mission set, and an optimal schedule for assigned CLF ships within the theater, enabling continuous logistic support throughout the planning horizon.

The logistics mission bears additional burdens on surface combatants because, in every scenario, supply ships are high-value units or mission-essential units, and they must be protected by the combatants.

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II. BACKGROUND

Every unit that is not supported is a defeated unit.

Maurice de Saxe: Mes Rèveries XIII, 1732

A. WHY IT IS MANDATORY TO PLAN LOGISTIC SUPPORT IN PARALLEL TO THE OPERATIONAL PLAN

Looking into the past of the 20th century, we find many examples of why sound logistic planning is of such importance for the success of military operations. Looking back as far as WWII, we observe the logistic shortfalls of the Axis powers throughout the entire war period. This imposed insurmountable restrictions to their military operations, which finally led to defeat and the end of the war.

Although Germany and Japan understood that resources, mainly crude oil, were mandatory to pursue their strategic goals, the operational tempo often left their logistic components trailing behind. Therefore, supplies of combat forces during offensive operations were decreased and logistic assets left vulnerable to enemy counterattacks. Even though both powers had military success in the early stages of the war, both were defeated decisively because of overstretched and unprotected supply lines and insufficient amounts of resources as a logical result of the ongoing attacks of allied forces against the enemy supply lines.

Looking into more detail of the German campaign, we find that logistic planning prior to the beginning operations was not deemed important as supplies were picked on the way during the assault on France. This enforced the mindset of German military commanders about the role of logistical planning even more, before starting the Russian and North African campaigns. However, despite all warnings by the logistic planners, both campaigns ended in defeat, and finally forced Germany back into its own territory. During the final stages of the war, when the lessons learned with respect to logistical planning were embraced, and

logistical planning was thoroughly conducted, Germany did not possess the means to support their combat forces. The small numbers of support units were furthermore decreased by ongoing attacks of U.S. Forces against unprotected German supply lines (Goralski & Freeburg, 1987).

Although the Japanese fate was similar to the German one at the end of the war, their road to defeat was a different one. Like Germany, Japan was driven by inadequate natural resources on its mainland. Also, similar to Germany, the Japanese Imperial Forces achieved military success in the early stages of their campaign. However, these early successes vastly increased Japanese-controlled area and thereby stretched the sea lines of communication between the occupied territories and Japan. Furthermore, disputes about disposition of fuel between the Army and the Navy led to shortfalls for combat units, which highly effected Japanese operations in the Pacific theater. After U.S. Forces started to attack their supply lines and tankers heading for Japan, the stock level of supplies depleted even faster. For example, insufficient supplies restricted Japanese ships to slower transit speeds in order to burn less fuel, enabling the ships to run at high speeds during engagements (Goralski & Freeburg, 1987).

The perfect example of adequate and thorough logistical planning can be found in the same epoch, when focusing on the European campaign of the U.S. Forces. During the allied operations, logistic requirements and considerations played a key role with respect to the operations tempo. Whenever necessary goals of the strategic plan, such as conquering an important seaport, could not be achieved without logistic support, operations were stalled until logistic support could be ensured. Therefore, means of support were frequently adjusted along with alterations to the operational plan, and due to the destruction of vital infrastructure (Goralski & Freeburg, 1987).

These examples precisely illustrate how flawed and/or uncoordinated logistic and operational planning lead to results not favorable to the outcome of a campaign, while the last shows the diametric opposite.

Returning to the present, we find lessons learned laid down in principal publications of several organizations. For example, the NATO logistic handbook says that the logistic planning staff needs to interact closely with the operational planning staff to ensure that logistic portions of the Concept of Operations (CONOPS) are *“realistic and properly coordinated”* (SNLC, 2007).

The USN doctrine publication for Logistics (NDP 4, 2001) carries the idea of concurrent planning a step further by stating that the result of the parallel planning process is a logistic concept of operations (CONOPS) that has the same level of importance as the operational CONOPS. During the different planning phases, logisticians are responsible for identifying requirements and potential bottlenecks, while being supported by operational planners.

B. OPERATIONAL PLANNING-PHASE MODEL

Operational mission planning today enables the force commander to understand the multiple threads that can be associated with one single military campaign. Furthermore, it helps the planning staff visualize interdependencies between different tasks within the entire campaign. JDP3-0 (2006) introduces a phasing model that supports planners in these tasks. Using different phases deconflicts overall planning and reveals insights on how to achieve military objectives most efficiently by using smaller arrangements. Additionally, phasing can be utilized to assess risks for smaller portions of the campaign.

The current phasing model includes five phases for operational mission planning as shown in Figure 1.

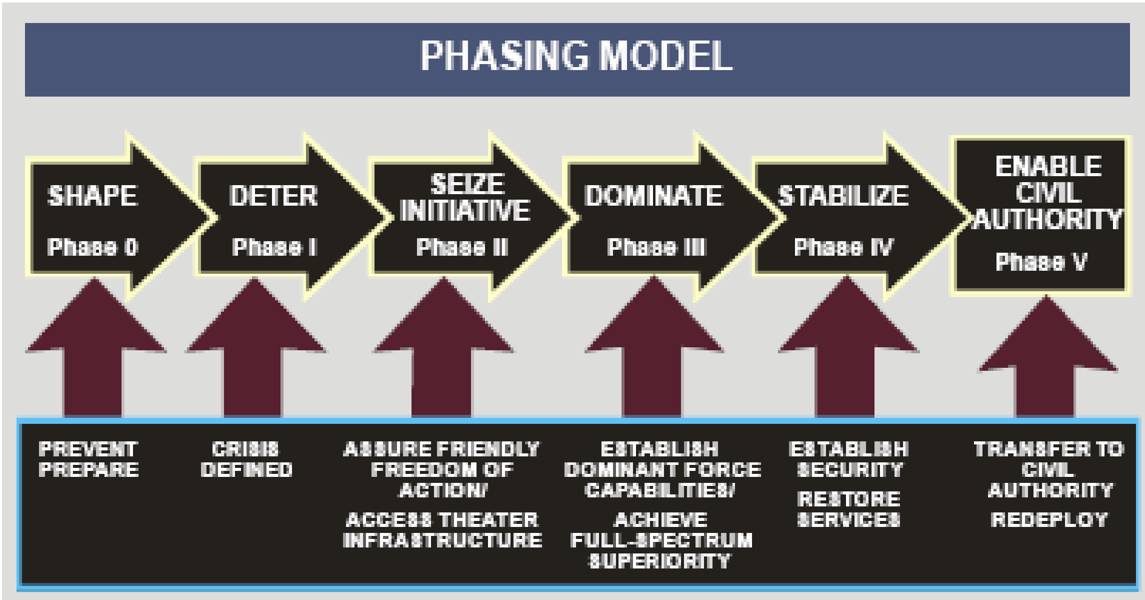

Figure 1 Operational planning phasing model
From (JDP3-0, 2006)

1. Phase 0 (Shape)

Shaping activities are related to a specific mission area and are conducted continuously. The common goal is to strengthen relationships with allies and friends as well as to enhance international legitimacy and multinational support. In short, this shaping prepares the theater of operations as well as the political community (JDP3-0, 2006).

2. Phase 1 (Deter)

This phase incorporates primary military operations in order to demonstrate the capabilities of the force. The spectrum of these operations starts from preliminary intelligence, surveillance, and reconnaissance to prepositioning of forces. The actions taken in this phase build on activities in the earlier phase (JDP3-0, 2006).

3. Phase 2 (Seize the Initiative)

Seizing the initiative includes application of military force enabling the conducting of offensive operations as early as possible. The military actions

taken in this phase can be regarded first, as preparation for decisive actions in the following phase, and second, to dislodge enemy positions from his earlier actions. It contributes to greater freedom of friendly movements and the establishment of stable conditions (JDP3-0, 2006).

4. Phase 3 (Dominate)

After the initial combat operations have stalled enemy operations, this phase is focused on breaking the capability for organized resistance. It employs the full spectrum of military force capabilities including decisive action to achieve mission objectives. Thereby, favorable conditions for an early conclusion of operations and upcoming phases of the campaign may be established (JDP3-0, 2006).

5. Phase 4 (Stabilize)

In this phase, the operations swing from sustained combat operations to stabilizing operations in order to maintain the military and/or political threat at a manageable level. This includes services to local authorities and the general population, if necessary. These services may include governance if no legitimate civilian entity is present, and support to nongovernmental or international organizations until civilian structures have been re-established. The end of this phase is reached when governing authority is handed over to local institutions (JDP3-0, 2006).

6. Phase 5 (Enable Civil Authority)

During this phase, the military end state is achieved and the end of the operations is reached. As during the stabilization phase, the force supports a legitimate local authority enabling the provision of essential services to the local population in order to maintain stability within the region (JDP3-0, 2006).

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III. COMBAT LOGISTIC FORCE (CLF) PLANNER – TRANSITION FROM A STRATEGIC TO AN OPERATIONAL DECISION AID

A. INTRODUCTION TO THE ORIGINAL CLF

The original version of the CLF planner was designed as a strategic decision aid studying the influence of composition and employment of the United States Navy (USN) CLF force and the resulting ability to support USN combat ships during their simultaneous worldwide operations. It uses integer linear programming to deterministically evaluate whether the anticipated missions are sustainable by the CLF, and to discover whether the available logistic support can sustain operations. It uses navigational tracks of each of its customer battle groups (BG) with daily fidelity over a planning horizon of 90–180 days to model CLF operations.

Additional data such as logistic consumption factors, speed, and maximum capacities of the CLF ships are embedded in a spreadsheet. Also incorporated is a global network of navigable sea routes (Figure 2) that is the foundation for CLF ship movements between their respective homeports and operation areas.

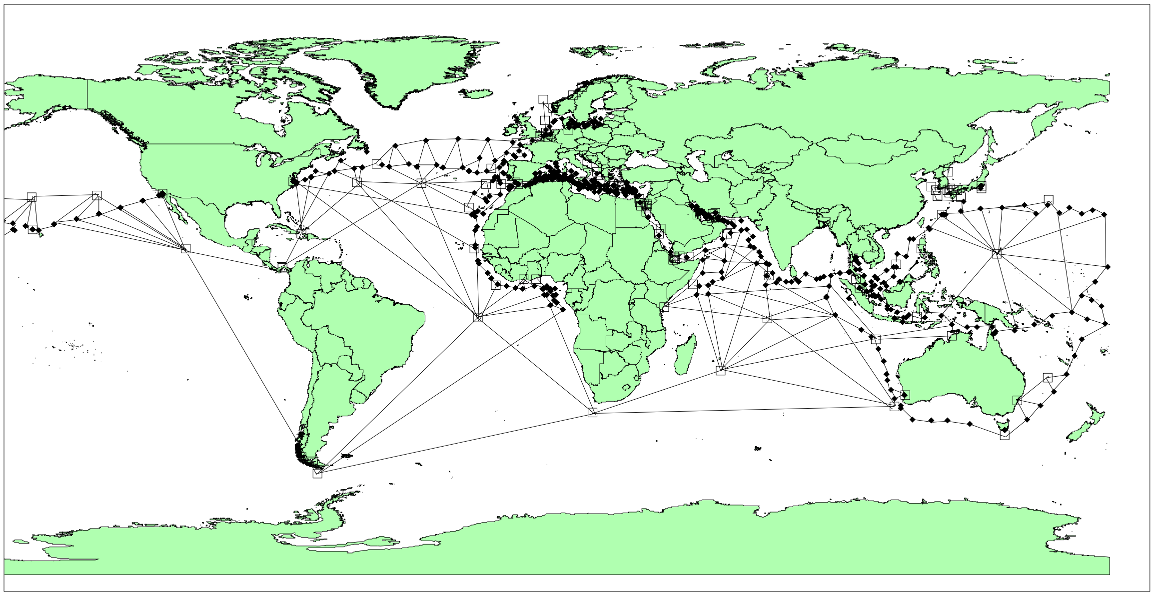

Figure 2 Sea Routes Network

The static sea routes network shows how the CLF ships can transit the world from their respective homeports to intercept BGs for underway replenishments. Figure from Doyle (2006)

The BG transit routes are overlaid onto the static sea routes network and are also assumed to be navigable by CLF ships. The sustainability of a BG is estimated by applying the consumption factors of four aggregated commodities. These are distillate fuel, marine (DFM), aviation fuel (JP5), all dry stores such as food items, spare parts, tools, etc. (STOR), and ammunition (ORDN). Furthermore, port availability for CLF ship classes as well as individual hull numbers of CLF ships may also be modeled.

The model provides valuable output in the form of optimized deployment schedules for CLF units and saw-tooth charts visualizing anticipated commodity levels for each commodity and individual customer BG. These plans consist of the day of replenishment, an estimated amount being transferred, as well as port visits by CLF ships to restock. The model determines whether a BG needs replenishment by comparing the estimated remaining capacities within the BG with a safety stock determined by the maritime Force Commander. Furthermore, it uses an even lower extremis level, if capacities fall below safety stock.

Inventories below safety stock or extremis level are penalized with respective penalty values the model seeks to minimize while generating the CLF deployment schedules (Brown & Carlyle, 2008).

B. THE ROAD TO THE CLF PLANNING TOOL

The CLF planner is a product of a series of Naval Postgraduate School Master's Theses in Operations Research. Previous work includes studies about the necessary number of ships of a particular CLF type to enable sustained support for BGs on their way into theater as well as different concepts of employing these assets (Borden, 2001). Borden concludes that 11 T-AKE are necessary to assure support for USN operations as defined by his scenarios. He also discovers that prepositioning CLF units, specifically the T-AKE, is an attractive alternative of pairing a T-AO and a T-AKE as station ships for a BG, however, this would restrict the BG's speed of advance.

Cardillo (2004) examines the level of logistic support, developing several concurrent scenarios, employing every available naval combatant, and considering activation of fleet naval reserve units. His findings are that even with unrestricted port availability within the AOO of his basic scenario, some BG fuel levels are inadequate to sustain operations. Further findings include that additional logistic support, especially during an inter-theater shift of the CLF ships, is necessary in order to sustain maritime military operations.

Further work focused on the issue of fleet ownership and control of CLF ships (Doyle, 2006). The USN numbered fleets command and control operations in assigned areas (Figure 3) worldwide. CLF units assigned to operations within these areas are temporarily controlled by the respective numbered fleet commander.

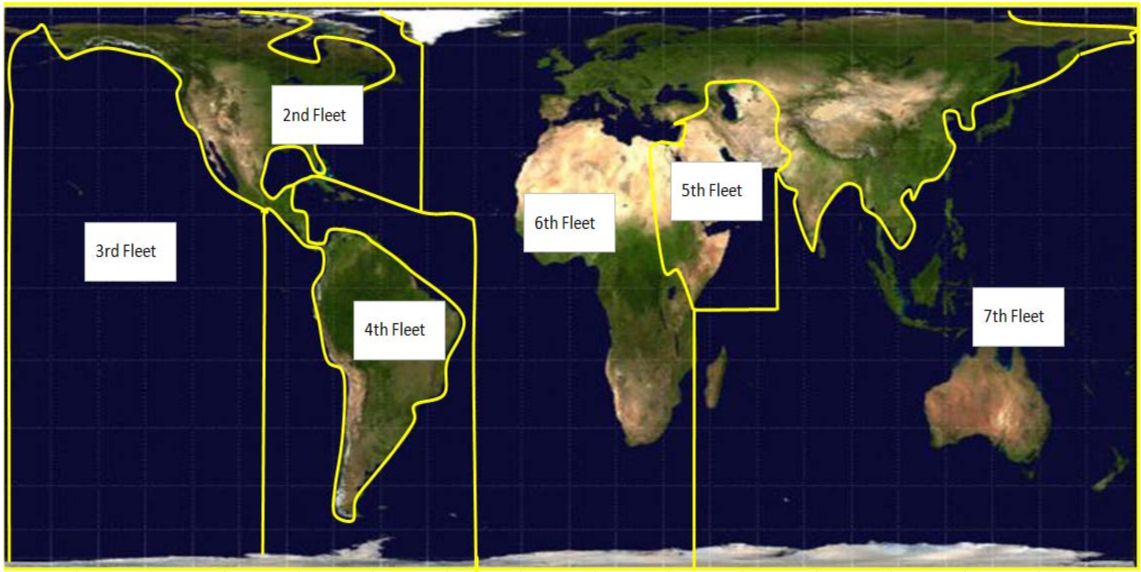

Figure 3 The Numbered Fleet Areas of Operations
From http://www.globalsecurity.org, 2000-2009

For example, a Henry J. Kaiser class T-AO that supports operations in the Persian Gulf region is assigned to 5th Fleet. However, if operating in the Mediterranean, she will be assigned to 6th Fleet. Doyle reveals that inflexible fleet ownership detracts from logistic support and CLF effectiveness if multiple concurrent maritime operations in multiple fleet ownership areas need to be supported.

C. THE CLF TRANSITION FROM A STRATEGIC TO AN OPERATIONAL PLANNING TOOL

CLF planner was chosen among other software applications by the Navy Warfare Development Command (NWDC) and 2nd USN Fleet to be evaluated within the Maritime Operation Center (MOC) during the execution of Trident Warrior 2009 (TW09), a synthetic fleet exercise primarily simulating the operations of a global fleet station in the Gulf of Guinea paired with global operations in the Mediterranean, the Atlantic, and the Caribbean. TW09 is primarily aimed to practice and improve interoperability as well as coordination between different MOC's situated in several locations in North America as well as

Europe. The anticipated application of the CLF planner required additional features and alterations to the existing functionalities of the planner.

D. THE OPERATIONAL CLF PLANNER MODEL

The original modeling formulation appears in Brown and Carlyle (2008). The following updated model incorporates necessary changes to account for the higher fidelity required for operational mission planning.

1. Indices [Cardinality]

$v \in V$ Class of shuttle ship [~5]

$s \in S$ Shuttle ship [~25]

$v(s)$ Class of shuttle ship s

$s \in S_v \subseteq S$ Shuttle ships in class v

$p \in P$ Port available to load shuttle ships [~35] (alias px)

$bg \in BG$ Battle group [~13] (alias bx, by)

$d \in D$ Day [~181] (alias dx, dy, dh)

$dp \in DP_{bg} \subseteq D$ Days a battle group visits some port to load commodities

$d_p \in D_{bg} \subseteq D$ Deployed days for battle group

$dh \in DH_{bg,d} \subseteq D$ For deployment day d, set of deployment days since the later of the start of the planning horizon and the latest port call.

$c \in C$ Commodity group (DFM, JP5, STOR, ORDN) [~4]

$\hat{c} \subseteq C$ Dry commodity subject to load fraction restrictions (STOR, ORDN) (alias $\hat{c}$)

For economy of exposition, we assume (bg,d) pairs are defined only for $d \in D_{bg}$

2. Provided Data [Units]

$spdSHUTTLE_s$ Speed of shuttle ship s [nm/day]

$inptTAT$ Time to reload shuttle ship in port [days]

$portok4s_{s,p}$ Binary indicator that shuttle ship s can reload at port p [binary]

$legdays_{s,bg,d,p}$ Shuttle ship *s* transit time at speed $spdSHUTTLE_s$ to or from bg position on day *d* and port *p* following given sea routes and/or BG tracks [days]

$cycledays_{s,bg,d,p,bx,dx}$ days required for shuttle ship s to depart bg on day d, reload at port p (or proceed directly), and then rendezvous with bx on day dx [days]

$directdays_{s,bg,d,bx,dx}$ The number of steaming days for shuttle s to transit from the position of bg on day d directly to the position of bx on subsequent day dx (i.e., without reloading in any port). (Policy limits may govern the minimum or maximum days allowed between these planned events.)

$useBG_{bg,d,c}$ Consumption by bg during day *d* of commodity c [*c*-units]

$mxload_{bg,c}$ Maximum capacity of bg to carry commodity c [*c*-units]

$init\_load_{bg,c}$ bg inventory of commodity c on first deployed day [*c*-units]

$init\_lat_s, init\_lon_s, init\_state_s$ optional pre-positioning of shuttle s either “empty” and requiring routing to a port, or “loaded” and requiring routing to a customer battle group.

$safety_c$ Minimum desired fraction of $mxload_{bg,c}$ to be held at all times [fraction]

$extremis_c$ Extreme minimum desired fraction of $mxload_{bg,c}$ to be held at all times, $extremis_c \le safety_c$ [fraction].

$hitOK_{bg,d}$ Logical indicator if bg can CONSOL on day d [binary]

$capacity_{s,c}$ Shuttle ship s capacity to deliver commodity c [*c*-units]

$mnfrac_{\hat{c}}, mxfrac_{\hat{c}}$ Minimum, maximum fraction of T-AKE dry capacity that must be loaded with dry commodity $\hat{c}$ [fraction]

$safety\_penalty_c$ Penalty per deficit unit of desired storage below safety-stock held by any BG [penalty per *c*-unit]

$extremis\_factor$ Multiplier (>1, e.g. 10) for penalty per deficit unit of desired storage below extremis held by any BG [dimensionless]

$negative\_factor$ Multiplier (> $extremis\_factor$, e.g. 1000) for penalty per deficit unit of desired storage below zero held by any BG [dimensionless]

win Minimum number of days between bg consol

3. Derived Data

$mxconsol_{s,bg,c}$ Maximum delivery shuttle ship *s* can make to bg on any day of commodity c [*c*-units]. This is defined as:

$\min\{mxload_{bg,c}, capacity_{s,c}\}$.

In addition, for T-AKE shuttle ships and dry commodities $\hat{c}$ sharing dry storage, and subject to limits on the minimum and maximum fractions of dry capacity that must be carried in every T-AKE load, this is restricted to:

$$\min\{mxload_{bg,c}, \min[mxfrac_{\hat{c}}, 1 - \sum_{\tilde{c} \ne \hat{c}} mnfrac_{\tilde{c}}] * capacity_{s,\hat{c}}\}$$

or, the maximum permitted T-AKE load of dry commodity $\hat{c}$, or the amount of commodity $\hat{c}$ that can be loaded after the minimum loads of other dry commodities $\tilde{c} \neq \hat{c}$ sharing dry storage are loaded.

$cycledays_{s,bg,d,p,bx,dx}$ gives the number of days required for shuttle ship s to depart bg on day d to reload at some port p (or proceed directly) and then rendezvous with bx on day dx :

$$\min\left\{ \infty, \min_{\substack{p| \\ portok4s_{s,p}}} \left[\min_{\substack{dx \geq legdays_{s,bg,d,p} \\ +inptTAT \\ +legdays_{s,bx,dx,p}}} \left(legdays_{s,bg,d,p} + inptTAT + legdays_{s,bx,dx,p} \right) \right] \right\}$$

Note that this admits a cycle with slack time (or, “shuttle waiting time”) $dx - d - cycledays_{s,bg,d,bx,dx} \geq 0$, and that because of the relative motion of a shuttle ship and a BG over navigable sea routes, and their daily proximity to ports and to each other, there will be cases in which planning for a shuttle to wait for this amount of time is better than restricting plans to have no such slack.

4. Decision Variables

$VISIT_{bg,d}$ Binary indicator that at least one shuttle visits bg on day d

$HIT_{s,p,bg,d}$ Binary indicator of shuttle s coming from port p to a CONSOL visit of bg on day d (depends on $hitOK_{bg,d}$) (One port is called “direct” and indicates that the associated CONSOL visit follows some prior one without an intervening port call to reload.) (Restriction of shuttle s initial location and state may preclude some *HIT* events. E.g., from some initial location, an empty shuttle would have to transit to a port, reload, then transit to a bg location by day d.)

$SLOAD_{s,d,c}$ Shuttle s commodity c contents at end of day d [*c*-units]

$CONSOL_{s,bg,d,c}$ Amount of shuttle s delivery to bg on day d of commodity c [c-units]

$SHORTAGE_{bg,d,c}$ Amount of inventory deficiency of c for bg, at end of day d [c-units]

$EXTREMIS_{bg,d,c}$ Amount of extreme deficiency of c for bg, at end of day d [c-units]

$NEGINV_{bg,d,c}$ Magnitude of negative inventory of c for bg at end of day d, has this [c-units]

5. Formulation

s.t.
$$SLOAD_{s,d-1,c} + \sum_{\substack{p\in P-\{direct\},\\ bg\in BG}} capacity_{s,c} HIT_{s,p,bg,d+legdays_{s,bg,d,p}} \geq \sum_{bg\in BG} CONSOL_{s,bg,d,c} + SLOAD_{s,d,c} \qquad \forall s\in S, d\in D-\{1\}, c\in C \qquad (1)$$

$$\sum_{\substack{s\in S,\\ dh\in DH_{bg,d}}} CONSOL_{s,bg,dh,c} \leq \sum_{dh\in DH_{bg,d}} useBG_{bg,dh,c} + [mxload_{bg,c} - init\_load_{bg,c}]_{d=argmin\{D_{bg}\}} \qquad \forall bg\in BG, d\in D_{bg}, c\in C \qquad (2)$$

$$\sum_{\substack{s\in S,\\ dh\in DH_{bg,d}}} CONSOL_{s,bg,dh,c} + SHORTAGE_{bg,d,c} + EXTREMIS_{bg,d,c} + NEGINV_{bg,d,c} \geq \sum_{dh\in DH_{bg,d}} useBG_{bg,dh,c} - (1-safety_c) mxload_{bg,c} \qquad \forall bg\in BG, d\in D_{bg}, c\in C \qquad (3)$$

$$CONSOL_{s,bg,d,c} \leq mxconsol_{s,bg,c} HIT_{s,bg,d} \qquad \forall s\in S, \forall bg\in BG, d\in D_{bg}, c\in C \qquad (4)$$

$$\sum_{p\in P} HIT_{s,p,bg,d} \leq 1 \qquad \forall s\in S, bg\in BG, d\in D \qquad (5)$$

$$HIT_{s,p,bg,d} + \sum_{\substack{bx \in BG, \\ px \in P, dx \in D_{bx} \\ |dx-d < cycledays_{s,bg,d,px,bx,dx}}} HIT_{s,px,bx,dx} \le 1 \qquad \forall s \in S, p \in P, bg \in BG, d \in D_{bg} \quad (6)$$

$$\sum_{\substack{s \in S_V, \\ p \in P, \\ d \le dx \le d+win}} HIT_{s,p,bg,dx} \le 1 \qquad \forall v \in V, bg \in BG, d \in D_{bg} \quad (7)$$

$$\sum_{\substack{p \in P, \\ bg \in BG}} HIT_{s,p,bg,d} \le 1 \qquad \forall s \in S, d \in D \quad (8)$$

$$\sum_{\substack{s \in S_V, \\ p \in P}} HIT_{s,p,bg,d} \le VISIT_{bg,d} \qquad \forall v \in V, bg \in BG, d \in D_{bg} \quad (9)$$

$$\sum_{p \in P} HIT_{s,p,bg,d} \le VISIT_{bg,d} \qquad \forall s \in S, bg \in BG, d \in D \quad (10)$$

$$\sum_{d-win \le dx \le d} VISIT_{bg,dx} \le 1 \qquad \forall bg \in BG, d \in D_{bg} \quad (11)$$

$$VISIT_{bg,d} \in \{0,1\} \qquad \forall bg \in BG, d \in D_{bg}$$

$$HIT_{s,p,bg,d} \in \{0,1\} \qquad \forall s \in S, p \in P, bg \in BG, d \in D_{bg}$$

$$0 \le SLOAD_{s,d,c} \le capacity_{s,c} \qquad \forall s \in S, d \in D, c \in C$$

$$0 \le CONSOL_{s,bg,d,c} \le mxconsol_{s,bg,c} \qquad \forall s \in S, bg \in BG, d \in D_{bg}, c \in C$$

$$0 \le SHORTAGE_{bg,d,c} \le (safety_c - extremis_c) * mxload_{bg,c}$$
$$\forall bg \in BG, d \in D_{bg}, c \in C$$

$$0 \le EXTREMIS_{bg,d,c} \le extremis_c * mxload_{bg,c} \qquad \forall bg \in BG, d \in D_{bg}, c \in C$$

$$0 \le NEGINV_{bg,d,c} \qquad \forall bg \in BG, d \in D_{bg}, c \in C \quad (12)$$

$$\underset{\substack{VISIT,HIT,\\SLOAD,CONSOL,\\SHORTAGE,EXTREMIS,NEGINV}}{\text{MIN}} \sum_{s\in S,bg\in BG,d\in D_{bg},c\in C} safety\_penalty_c * CONSOL_{s,bg,d,c}$$
$$+ \sum_{bg\in BG,d\in D_{bg},c\in C} safety\_penalty_c * SHORTAGE_{bg,d,c}$$
$$+ \sum_{bg\in BG,d\in D_{bg},c\in C} extremis\_factor * safety\_penalty_c * EXTREMIS_{bg,d,c}$$
$$+ \sum_{bg\in BG,d\in D_{bg},c\in C} negative\_factor * safety\_penalty_c * NEGINV_{bg,d,c} \qquad (13)$$

6. Discussion

Inequalities (1) account for shuttle cargo contents day by day. Inequalities (2) limit day-by-day cumulative CONSOL volumes of each commodity to the cumulative usage of each BG through the end of that day. We assume that on the first planning day, each BG contains some stated initial load quantity. Thereafter, daily use is deducted, and replenishments from port calls of those commodities offered and shuttle CONSOLs are added. Elastic inequalities (3) reckon cumulative inventory state of each commodity at the end of each planning day, and compare this to the cumulative usage less desired safety-stock level at the end of that day, representing any shortage, extreme shortage, or negative inventory required to reconcile this state. Each inequality (4) limits the CONSOL volume transferred from a shuttle ship, to a BG, on some given day, to be zero unless a replenishment event takes place. Constraints (5) allow at most one port source for each CONSOL. This “port” may be “direct,” indicating no preceding port call. Constraints (6) restrict successive shuttle rendezvous with battle groups so that each such visit is followed by sufficient time to cycle to a port for re-supply. Each constraint (7-11) permits a shuttle to engage in at most one activity on a given day. Variable domains are stated by constraints (12). The objective (13) expresses a penalty with a component for any shortage below safety-stock, extreme shortage below minimum stock, and any negative inventory as well as less rewards for commodity volume delivered. The rewards here are 10 percent of the safety stock shortage penalties, and attract maximal delivered volumes, rather than merely deliveries to avoid

shortages. The model can schedule a single shuttle ship sortie from port to make many separate CONSOL visits, perhaps to different battle groups.

E. ENHANCED FEATURES OF THE OPERATIONAL PLANNING INSTANCE OF CLF

The following paragraphs highlight the CLF embellishments introduced here for operational logistic planning.

1. Sea Routes Network and Ports

Major updates have been made to the static sea routes network (Figure 4). More than 100 ports have been added, along with 350 more nodes, which result in over 550 new navigable arcs. Besides the sheer increase in the number of ports, we also now model limited availability of each of the four main commodities in these ports. Earlier features restricting availability of ports for entire classes of CLF ships down to individual hull numbers remain. Additionally, BGs that enter a port can be restocked such that replenishments by CLF ships just before a BG's port visit or shortly thereafter may be unnecessary.

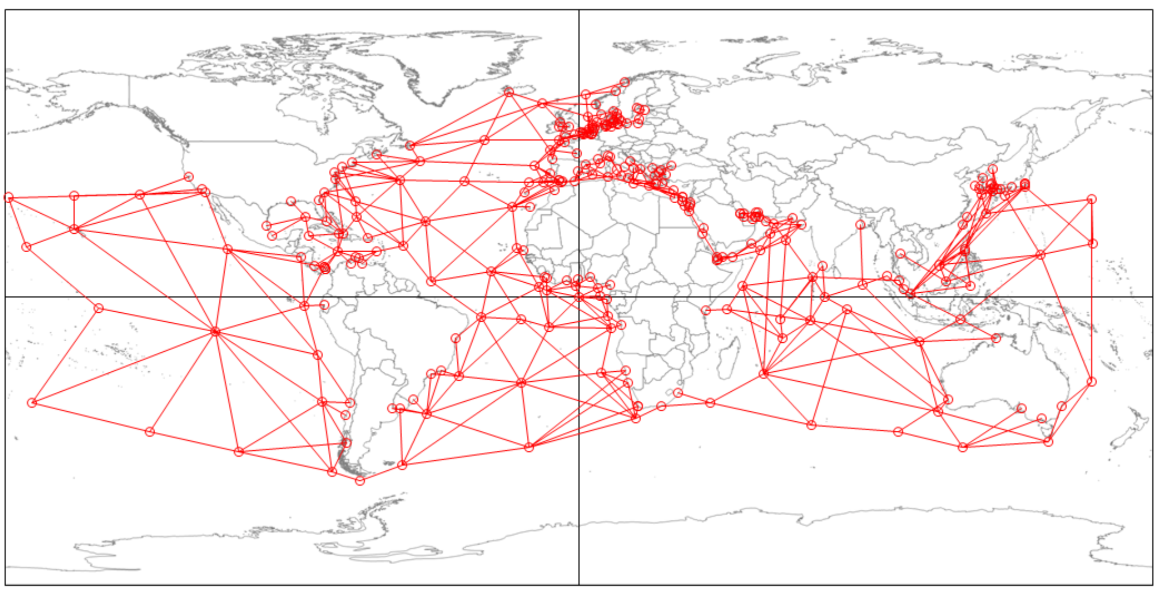

Figure 4 New Sea Routes Network
The new sea routes network exhibits the increased fidelity compared to Figure 2.

2. Force Composition and Activation

A complete catalog of every active USN ship has been added, combatant as well as CLF, which enables the planner to insert ships directly associated with the scenario by hull number and name. Additionally, instead of having BGs and CLF ships start at the first day of the overall planning horizon, the model now is able to account for BGs that arrive later in an AOO, or become active at a later point in time due to other commitments such as overhaul, maintenance, or transfer from a different operation not accounted for by the model. Furthermore, BGs may leave the operation before the planning horizon expires.

3. Dashboard Functionalities

The “dashboard” in the Microsoft Excel interface has also been polished. The number of available maps of possible geographic operation areas has been increased to provide more views and more scales of views worldwide. Moreover, various display options are included in the maps allowing a planner to precisely demonstrate possible courses of action (COA) and the resulting implications. For example, besides nodes, ports and sea routes, the model now displays the BG navigational tracks and the CLF ship navigational tracks. Furthermore, we can display the exact position of an underway replenishment between a CLF ship and a BG anywhere on the planet. Ports utilized by CLF ships to restock their inventory levels are displayed as well.

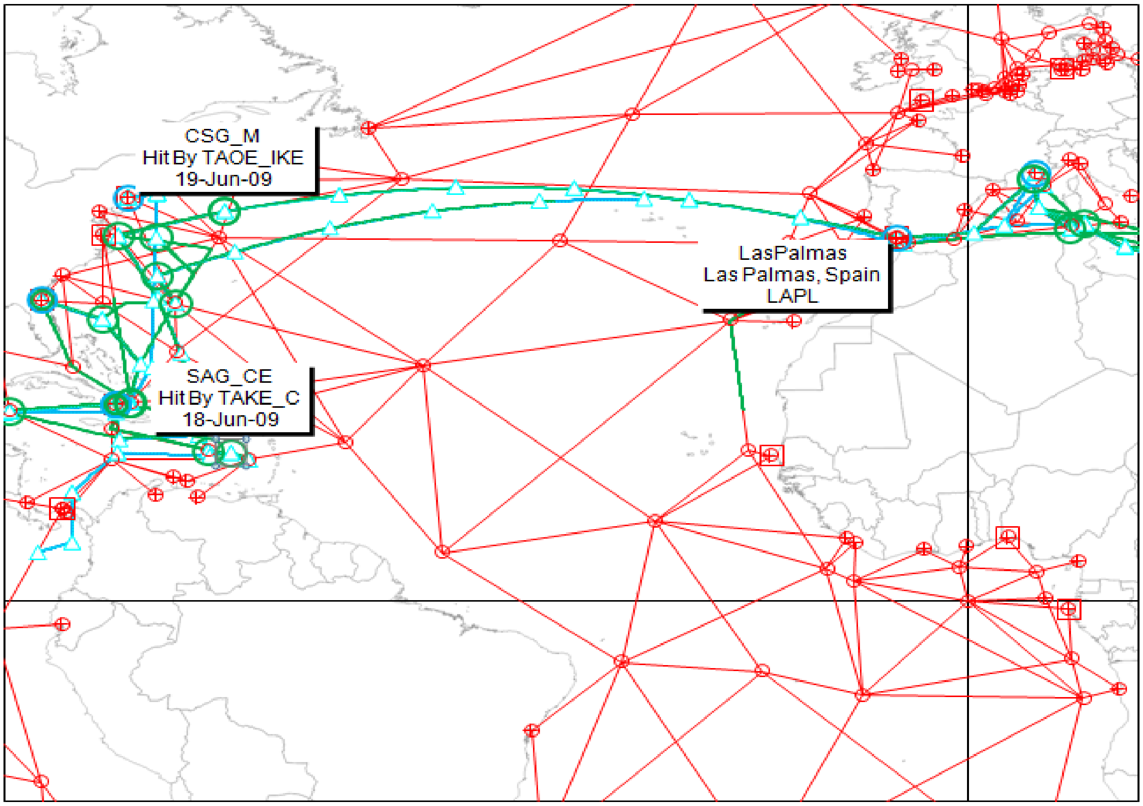

Figure 5 Enhanced CLF visualization

This shows the new display functionality in the operational CLF planner, here the North Atlantic region. The display feature is in color. Red (darkest) lines represent the arcs, red circles represent nodes, red crosshairs are available ports. Green (light) lines visualize CLF ship movements, and green circle shows underway replenishment with a customer BG. Turquoise (very light displayed) triangles are daily BG positions, and similar colored lines are BG tracks. Blue circles indicate that the port was used by a CLF ship to restock commodities. The data boxes can be activated by clicking on any feature.

4. Shuttle Ship Operations

Our *operational* plans now address smaller BGs than the legacy strategic plans involving large carrier battle groups. Now we deal with BGs that may consist of individual ships. Accordingly, where before CLF assumed a shuttle ship would transfer all its cargo in a single consolidation (CONSOL), or perhaps two, now we allow a shuttle to make an unlimited number of consolidations until the model decides to make a replenishment port call. A consolidation is considered as an event where a CLF ship rendezvous with a BG to replenish the BGs station ship or the entire BG.

5. Animation

We have equipped CLF with an animation feature to illustrate the time and location dynamics of suggested plans on any of a catalog of world maps. The animation is very helpful to visualize the synchronized movements of shuttles among the also-moving BG customers.

6. Employment States

Many more alternate types of employment states have been introduced to better represent the rate at which BGs consume commodities. For instance, a BG might engage in “light,” “medium,” or “heavy” flight operations, influencing JP5 consumption.

F. TRIDENT WARRIOR 2009 (TW09) – OPERATIONAL PLANNING WITH THE CLF PLANNER

Trident Warrior is an annual operational command and control exercise hosted by the USN and Naval Network Warfare Command (NNWC). The scope of the 2009 experiment is to evaluate new technologies, tactics, techniques and doctrines enhancing the capabilities of the war fighter at sea by using committed assets from 2nd U.S. fleet (i.e., USS KEARSARGE (LHD3), USS NORMANDY (CG60), USS FARRAGUT (DDG99), USS BULKELEY (DDG84), and USS ALEXANDRIA (SSN757)) as well as a worldwide network of maritime command centers (Poeltler et al., 2008).

1. Baseline Scenario

The setting for TW09 incorporates two major operating areas situated in the Gulf of Guinea and the Caribbean with additional operations in the Mediterranean and off the U.S. East coast. The full scenario consists of 17 BGs composed of 34 ships of various classes such as aircraft carriers, large-deck amphibious ships, cruisers, destroyers, frigates, and Coast Guard cutters as well as six CLF ships, for example, fleet replenishment oilers, modular dry cargo ammunition ships, and fast combat supply ships. The size of a BG ranges from a

full-scale carrier battle group to a single ship conducting individual mission assignments. Special focus is on a large-deck amphibious ship acting as a Global Fleet Station in the Gulf of Guinea. This ship is operating to support coastal West African states by conducting a variety of missions such as construction work (e.g., building schools and roads), intra-theater security support, and medical aid. The time horizon of the operation extends over 180 days, starting on April 1, 2009, and ending October 6, 2009.

2. CLF Optimization Results

Necessary input for the CLF planner such as daily BG navigational tracks, initial load outs for each commodity of each respective BG and CLF ship, and assignment of CLF ships to one or multiple BGs are defined by the given scenario. During the course of the exercise the operational logistics planning cell actively used the CLF planner to evaluate logistic sustainability of different operational courses of action.

The CLF planner is installed on a WINTEL Laptop with 2 GB RAM using the General Algebraic Modeling Software (GAMS) and the commercial CPLEX solver and solves times of about four minutes. The scenarios used during Trident Warrior generate mixed integer programs with about 5500 constraints, 6000 variables of which 1200 binary variables. After each solution, the optimization generates a deployment plan for the active CLF ships showing where and when a CLF ship replenishes a BG or makes a port call to re-stock its own inventory. Furthermore, this deployment plan shows the quantity of each commodity transferred (Table 1). Additionally, the BG daily state table (Table 2), an output spreadsheet containing inventory levels for each commodity and information on replenishments per BG, provides invaluable support for the both, the logistics and operational planner. Moreover, this output helps to identify whether, for instance, minor changes to a port visit schedule may have a major impact to the logistic sustainability of an anticipated course of action (COA).

Shuttle Schedule ☐ Apply Filters

State	Shuttle	Date	Coordinates	Where	DFM	JP5	STOR	ORDN	DFM	JP5	STOR
direct	TAO_M	19-Jun-09	N 35 28 48 E 24 10 40		72,000.0	108,520.0	220.0	0.0			
direct	TAO_M	20-Jun-09			72,000.0	108,520.0	220.0	0.0			
direct	TAO_M	21-Jun-09			72,000.0	108,520.0	220.0	0.0			
direct	TAO_M	22-Jun-09			72,000.0	108,520.0	220.0	0.0			
direct	TAO_M	23-Jun-09			72,000.0	108,520.0	220.0	0.0			
direct	TAO_M	24-Jun-09			72,000.0	108,520.0	220.0	0.0			
hit	TAO_M	25-Jun-09	N 35 57 00 W 05 45 00	CSG_M	72,000.0	108,520.0	220.0	0.0	12,294.0	18,090.0	158.8
direct	TAO_M	26-Jun-09			59,706.0	90,430.0	61.2	0.0			
idle	TAO_M	27-Jun-09			59,706.0	90,430.0	61.2	0.0			
hit	TAO_M	28-Jun-09	N 42 30 00 E 05 45 00	ESG_LM	59,706.0	90,430.0	61.2	0.0	29,571.6	2,638.0	51.2
direct	TAO_M	29-Jun-09			30,134.4	87,792.0	10.0	0.0			
direct	TAO_M	30-Jun-09			30,134.4	87,792.0	10.0	0.0			
direct	TAO_M	1-Jul-09			30,134.4	87,792.0	10.0	0.0			
hit	TAO_M	2-Jul-09	N 33 30 00 E 29 42 13	SAG_MW	30,134.4	87,792.0	10.0	0.0	12,776.4	258.0	10.0
direct	TAO_M	3-Jul-09			17,358.0	87,534.0	0.0	0.0			
direct	TAO_M	4-Jul-09			17,358.0	87,534.0	0.0	0.0			
direct	TAO_M	5-Jul-09			17,358.0	87,534.0	0.0	0.0			
idle	TAO_M	6-Jul-09			17,358.0	87,534.0	0.0	0.0			
hit	TAO_M	7-Jul-09	N 42 30 00 E 38 00 00	SAG_ME	17,358.0	87,534.0	0.0	0.0	8,488.0	380.0	0.0
inbound	TAO_M	8-Jul-09			8,870.0	87,154.0	0.0	0.0			

Table 1 Shuttle Schedules

This shuttle schedule from the CLF interface is an excerpt of 20 days. It shows the employment state and inventory levels of the CLF ship, the replenished BGs and CONSOL positions, including the calculated transferred amount per commodity.

BG Daily State ☐ Apply Filters

BG	Date	Coordinates	DFM	JP5	STOR	ORDN	HitType	HitBy	DFM	JP5	STOR	ORDN
CSG_M	15-Jun-09	N 36 47 48 W 74 56 45	85.0%	85.0%	85.0%	85.0%	consol	TAOE_IKE	1,639.2	4,057.0	59.0	5.3
CSG_M	16-Jun-09	N 36 47 48 W 74 56 45	80.5%	79.7%	81.9%	84.7%						
CSG_M	17-Jun-09	N 36 47 48 W 74 56 45	89.5%	90.3%	88.1%	85.3%	consol	TAOE_IKE	4,917.6	12,171.0	177.0	16.0
CSG_M	18-Jun-09	N 36 47 48 W 74 56 45	85.0%	85.0%	85.0%	85.0%						
CSG_M	19-Jun-09	N 39 14 29 W 65 33 38	100.0%	100.0%	97.5%	86.1%	consol	TAOE_IKE	7,459.2	14,425.1	295.0	21.4
CSG_M	20-Jun-09	N 40 51 58 W 55 26 50	94.3%	96.0%	94.4%	86.1%						
CSG_M	21-Jun-09	N 41 39 15 W 45 12 26	88.6%	92.1%	91.3%	86.1%						
CSG_M	22-Jun-09	N 41 31 31 W 34 47 17	83.0%	88.1%	88.1%	86.1%						
CSG_M	23-Jun-09	N 40 21 29 W 24 38 06	77.3%	84.2%	85.0%	86.1%						
CSG_M	24-Jun-09	N 38 37 43 W 14 51 22	71.6%	80.2%	81.9%	86.1%						
CSG_M	25-Jun-09	N 35 57 00 W 05 45 00	100.0%	100.0%	87.2%	86.1%	consol	TAO_M	12,294.0	18,090.0	158.8	0.0
CSG_M	26-Jun-09	N 37 50 09 E 03 05 04	94.3%	96.0%	84.0%	86.1%						
CSG_M	27-Jun-09	N 42 30 00 E 05 45 00	88.6%	90.7%	80.9%	85.0%						
CSG_M	28-Jun-09	N 42 30 00 E 05 45 00	83.0%	85.4%	77.8%	83.9%						
CSG_M	29-Jun-09	N 42 30 00 E 05 45 00	77.3%	80.0%	74.7%	82.8%						
CSG_M	30-Jun-09	N 42 30 00 E 05 45 00	71.6%	74.7%	71.5%	81.7%						
CSG_M	1-Jul-09	N 42 30 00 E 05 45 00	100.0%	100.0%	90.7%	87.2%	consol	TAOE_IKE	12,294.0	23,300.0	421.0	128.4
CSG_M	2-Jul-09	N 43 07 00 E 05 54 00	98.9%	100.0%	87.6%	87.2%						
CSG_M	3-Jul-09	N 43 07 00 E 05 54 00	97.7%	100.0%	84.5%	87.2%						
CSG_M	4-Jul-09	N 43 07 00 E 05 54 00	96.6%	100.0%	81.3%	87.2%						
CSG_M	5-Jul-09	N 43 07 00 E 05 54 00	95.5%	100.0%	78.2%	87.2%						
CSG_M	6-Jul-09	N 39 37 12 E 06 08 07	100.0%	100.0%	75.1%	93.8%	consol	TAOE_IKE	3,688.2	3,015.0	0.0	128.4

Table 2 BG daily state

The BG Daily State table shows the daily position of a BG and the inventory levels of all ships of the BG aggregated to one value. We see the example of a carrier BG over 22 days. Furthermore, we can obtain information on replenishments (i.e., which CLF ship and the amount of commodities) which represents the results of the optimization.

An accompanying saw-tooth diagram displays whether a COA is supportable, or if ships will drop below the designated inventory thresholds. We can easily observe in Figure 6 that the suggested COA is supportable within the time horizon and with respect to DFM. We see that two BG's drop close to or just below the extremis inventory level, but receive supplies shortly thereafter. For isolated information on each active BG and the other commodities, the planner can chose a BG from a drop down list in the Excel interface.

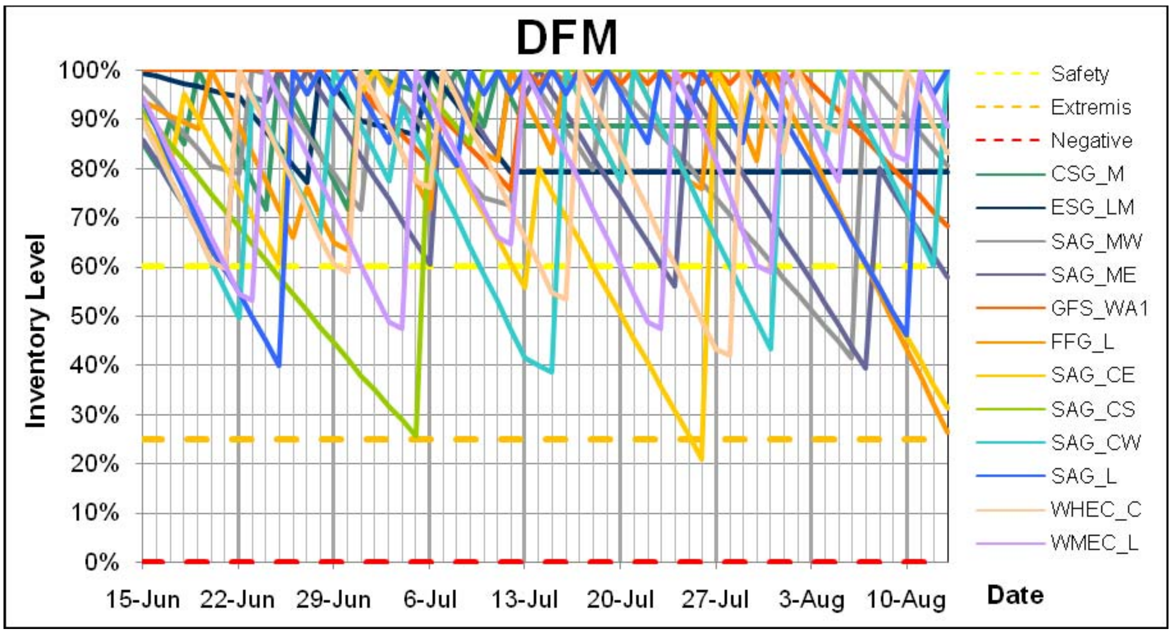

Figure 6 Saw-tooth Diagram

This intentionally overloaded saw-tooth diagram shows the DFM inventory level for each active BG in a different color for 59 days of the planning horizon.

The introduced animation feature was frequently used by the Trident Warrior 2009 logistic planning cell to display the dynamic movements of BGs and CFL ships to the operational planners and decision makers. This added feature in combination with the saw-tooth diagram and the generated output tables provides a valid, comprehensible, and integral element to the overall evaluation of one or multiple COA's and operational decision process. Figure 7 shows a display of the animation feature as implemented in the CLF Excel Interface.

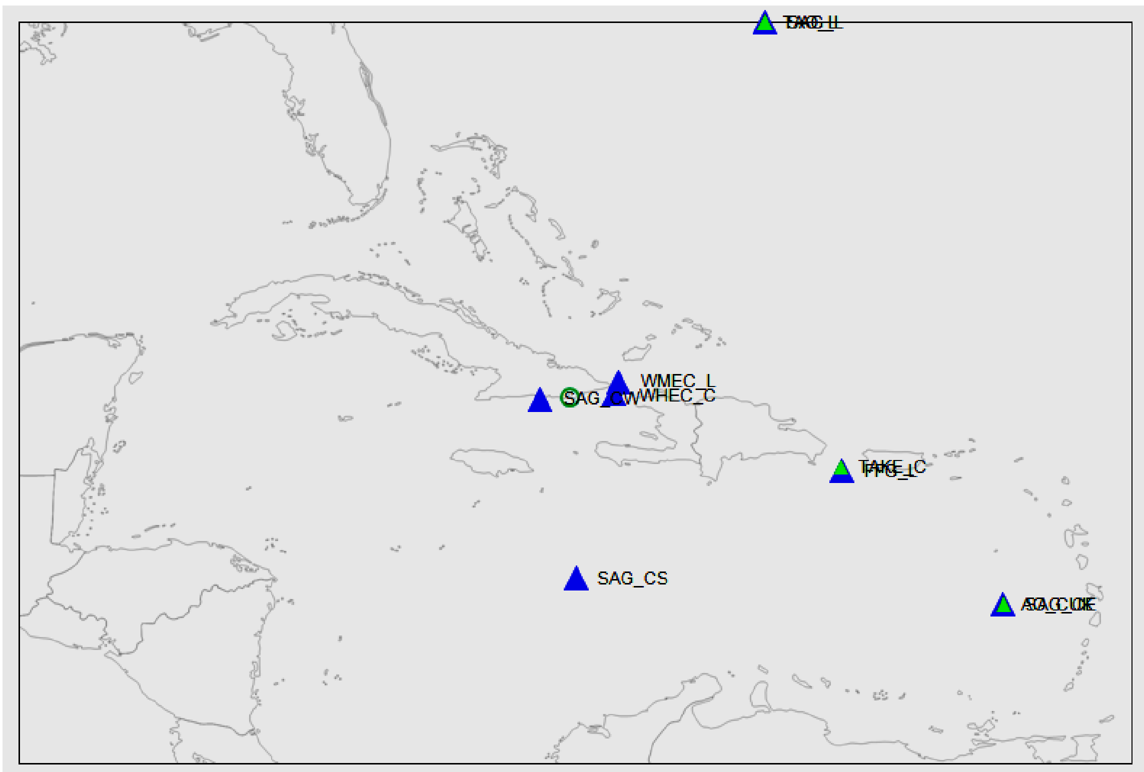

Figure 7 Animation

This shows a close-up look at the animation feature in the Caribbean AOO. The original feature is colored and displayed triangles represent different ships. The blue (dark) triangles represent combat ships while the green (light) triangles are CLF ships. A CONSOL is represented by overlaying triangles. The picture was formatted to enhance visibility of landmasses.

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IV. MODELING COMBINED OPERATIONAL AND LOGISTICS PLANNING

A. AN INTRODUCTION TO THE ORIGINAL NAVAL MISSION PLANNER (NMP)

The Navy Mission Planner (Dugan, 2007) is an automated decision support tool that uses mathematical optimization to seek the optimal daily employment schedule for surface and subsurface combatants of the USN on the operational level for a given planning horizon. It takes a predefined set of daily maritime missions located in each region of the AOO, along with the capabilities of each individual ship, and assigns the ships into predefined regions of a confined AOO such as the Korean Peninsula or the Mediterranean. It has the ability to assign multiple concurrent mission sets to a single ship depending on the operational capabilities of this particular unit. For example, a CG assigned to a region within the AOO could conduct air defense (AD), while also being assigned to surface warfare (SUW), maritime interdiction operations (MIO), STRIKE, and INTEL, or this ship could conduct any of a number of combined mission sets (CMC). At the same time, the planner also has the option to define mission dependencies such a mine counter measure (MCM) operation necessary prior to the passage of a narrow straight.

Additional inputs to the predefined mission set and the ship capabilities are the duration of each mission requirement for each region as well as the priority of the mission. With this information, the NMP seeks the best daily employment schedule for the available units.

Silva (2009) modifies the original NMP, enhancing the overall performance of the tool. Instead of using a static set of detached regions within an AOO, Silva introduces a network representation of the AOO. He enables the planner to flexibly assign ships within the AOO, calculate the shortest distance between adjacent nodes representing region locations, and easily determine the shortest transit times between regions. Using the network representation enables the

planning tool to use shortest paths (Ahuja et al., 1993), which decreases the overall computation time significantly.

NMP still seeks the optimal feasible daily deployment plan for the available units for each region and each day in the planning horizon. But, instead of using manual enumeration, the model now uses automated constrained enumeration. This implies that a global optimal solution for the scheduling problem might not be found, however, the advantages with respect to runtime and practicability weigh heavier. Nevertheless, the planning tool still produces near-optimal schedules that are more useful to the planner, because it is not necessary to search through an enormous amount of schedules in order to determine which one to use (Silva, 2009).

B. MODELING LOGISTICS – GENERAL CONSIDERATIONS

1. Input factors

In order to capture inherent characteristics of maritime operations, the optimization model requires several factors on which it bases its calculations for the optimized deployment schedules. The model consists of five major input categories.

a. Time

The necessary time input by the planning staff is (1) the planning horizon, and (2) the time fidelity of planning. The planning horizon constitutes the duration of the entire operation. The time fidelity of planning describes the detail, say if the steps of planning are hourly, daily, or weekly.

b. Geography

The planning tool requires the geographic boundaries of the AOO (e.g. the Arabian Peninsula, the Baltic, or the Korean Peninsula). Furthermore, the planner must divide the AOO into smaller operating areas over which a ship can be expected to fulfill missions, or simply regions.

c. Commodities

Similar to earlier studies, we will aggregate the individual material classes into four main commodity groups:

1. DFM (distillate fuel marine, NATO F75/F76)
2. JP-5 (aviation fuel, NATO F44)
3. Stores (aggregates all dry stores such as food items, spare parts, tools, etc.)
4. Ordnance (aggregates all ammunition)

d. Units

Each ship is defined by its respective type, which is associated with its capabilities, and consumption factors. The planner has to define the specific combat and supply ships anticipated to participate in the operation.

e. Consumption Factors

Each unit and each mission assignment have distinct consumption factors for each of the four commodities, depending on the crew size and the employment state of a ship. Depending on the phase of the operation, ships will conduct different missions, which requires different specific systems (e.g., fire control radar, weapon system, additional propulsion) to be online, while other deployment states just require standard systems (e.g., navigation radar, propulsion) to be available. Therefore, consumption will rise as soon as a ship conducts intensive missions such as strike or air defense. The implemented consumption factors are linked to different phases in the operation

f. Inventory Thresholds

The logistics portion of the model is driven by the consumption of commodities. Given the maximum inventory level for each commodity the planner has to define a safety stock level (e.g., at 60 percent of capacity) and an extremis stock level (e.g., at 25 percent). These thresholds are associated with a

penalty value within the model ensuring urgent support for these units. These inventory thresholds are set at commander's discretion, depending on the campaign, availability of CLF units, and area of operations.

C. AN INTEGER LINEAR PROGRAM TO OPTIMIZE NAVY MISSION PLANNING: NMP AND LOGISTIC SUPPORT

The model presented here derives from the purely operational planner, NMP introduced by Dugan (2007) and the embellished version introduced by Silva (2009). The logistic portion of the new planning tool is inspired by the CLF planning tool (Brown & Carlyle, 2008).

The following integer linear program, NMP with logistics, seeks the best achievable set of combat and CLF ship deployment schedules.

1. Sets and Indices [Cardinality]

$s \in S$	Ship (hull number and name, alias s') [~50]
$s \in CS \subseteq S$	Combatant ship [~40]
$s \in SS \subseteq S$	Supply ship [~10]
	($CS \cap SS = \Phi$, $CS \cup SS = S$)
$m \in M$	Mission type (alias m') [~12]
	(e.g., ASW, AAW, NSG, …, CAN_HIT, ESCORT, CLOSE_ESCORT)
$c \in C_s$	Combined mission capability set for ship s [~10]
$m \in M_c$	Mission types in combined (simultaneous) mission set c
	(e.g., ship s can simultaneously perform mission types m in combined mission capability set c.
$p \in P$	Employment schedules [~1 million]

$p \in P_s \subseteq P$	Employment schedules for ship s [~1 million]
	($\bigcup_s P_s \equiv P$, P_s is a partition of P.)
$s(p)$	Ship of employment schedule p
$r \in R$	Regions in AOO [~30]
$r \in R_{SS} \subseteq R$	Subset of regions navigable by supply ships [~25]
$r \in R_{SSX} \subseteq R_{SS}$	Supply ships in these regions must have combatant escorts [~25]
$d \in D$	Days in planning horizon (alias d', d'') [~14]
$r(p,d)$	Region employment schedule p visits on day d
$\{d, d'\} \in D_p$	Deployment schedule p for supply ship $s(p)$ has routes that can begin and end deliveries in epochs defined by these days
$n \in N$	Ordinal for multiple missions of the same mission type [~5]
	(E.g., several ships may conduct ASW at the same time within the same region, but with different effectiveness.
$\{m, m'\} \in Q_{r,d}$	In region r on day d, mission m can be undertaken only if mission m' is fully accomplished
$i \in I$	Commodity category (e.g., DFM, JP5, STOR, ORDN)

2. Data [Units]

$value_{m,n,r,d}$	Priority of n-th mission of type m, in region r on day d [1-10] [value]
	($\{m,n,r,d\} \in MNRD$ tuples exist only for non-zero values)

$accomplish_{c,m}$	Level of accomplishment of combined mission set $c \in C_s$, mission $m \in M_c$ [0.0-1.0] (Note that each ship may have its own set of combined mission capability sets, and that some of these sets may contain the same missions, but with different accomplish rates to represent the ship choosing to change emphasis between missions.)
$cap_{s,i}$	Capacity of ship s for commodity category i [i-units]
$init\_load_{s,i}$	Initial load of ship s, commodity i [i-units] ($init\_load_{s,i} \leq cap_{s,i}$)
$use_{s,c,i}$	Daily consumption of commodity i by combatant s employing combined mission capability c. [i-units]
$safety_i$	Safety stock fraction of capacity for commodity i [fraction]
$extremis_i$	Extremis stock fraction of cargo category i [fraction] ($0 < extremis_i < safety_i < 1$)
pen_safe_i	Penalty per unit of violation of safety stock for commodity i [value/i-unit]
pen_extr_i	Penalty per unit violation of extremis stock for commodity i [value/i-unit]
pen_out_i	Penalty per unit violation below zero stock for commodity i [value/i-unit] ($pen\_out_i > pen\_ext_i > pen\_safe_i > 0$)

use_supply_ships Indicates that supply ship employment scheduling and combatant commodity inventories should be included in employment plan [binary]

close_escort_required Indicates that every supply ship needs close escort every day it is deployed [binary]

3. Induced Index Sets

$\{m,n,r,d\} \in MNRD$ 4-tuple exists only if $value_{m,n,r,d} > 0$ or $accomplish_{s,m} > 0$ for some ship that can employ a combined mission capability set that includes mission m in region r on day d

$\{m,r,d\} \in MRD$ 3-tuple exists only if $\{m,n,r,d\} \in MNRD$ does for some n

4. Variables [Units]

$U_{m,n,r,d}$ Level of accomplishment of the n-th mission type m assignment in region r on day d [0.0-1.0]

$V_{m,r,d}$ = 1 if mission m is fully accomplished in region r on day d [binary]

$W_{s,c,r,d}$ = 1 if ship s employs combined mission capability c on day d [binary]

$X_{s,s',r,d}$ = 1 only if ships s and s' are both in region r on day d [binary]]

Y_p = 1 if schedule p is selected [binary]

$XFER_{s,s',d,i}$ Volume of commodity i transferred from supply ship s to combatant s' on day d [i-units]

$LOAD_{s,d,i,d',d''}$ Volume of commodity i transferred from supply ship s on day d during deployment from days d' to d'' [i-units]

$SLACK_{s,d,i}$ Combatant s, day d, commodity i stock in excess of safety-stock

[i-units]

$V\_SAFE_{s,d,i}$ Violation of safety stock level for combatant s, day d, commodity i [i-units]

$V\_EXTR_{s,d,i}$ Violation of extremis stock level for combatant s, day d, commodity i [i-units]

$V\_OUT_{s,d,i}$ Violation of positive stock level for combatant s, day d, commodity i [i-units]

5. Formulation

$$\begin{aligned} \max \quad & \sum_{\{m,n,r,d\}\in MNRD} value_{m,n,r,d} U_{m,n,r,d} \\ & - \sum_{s\in CS, d\in D, i\in I} pen\_safe_i V\_SAFE_{s,d,i} \\ & - \sum_{s\in CS, d\in D, i\in I} pen\_extr_i V\_EXTR_{s,d,i} \\ & - \sum_{s\in CS, d\in D, i\in I} pen\_out_i V\_OUT_{s,d,i} \end{aligned} \qquad \text{(T0)}$$

$$\text{s.t.} \quad \sum_{p\in P_s} Y_p \le 1 \qquad \forall s \in S \qquad \text{(T1)}$$

$$\sum_{c\in C_s} W_{s,c,r,d} = \sum_{\substack{p\in P_s \\ r=(p,d)}} Y_p \qquad \forall s \in CS, r\in R, d\in D \quad \text{(T2)}$$

$$\sum_{n|\{m,n,r,d\}\in MNRD} U_{m,n,r,d} \le \sum_{s\in CS, c\in C_s} accomplish_{c,m} W_{s,c,r,d} \qquad \forall \{m,r,d\} \in MRD \qquad \text{(T3)}$$

$$V_{m,r,d} \le \sum_{n|\{m,n,r,d\}\in MNRD} U_{m,n,r,d} \qquad \forall\{m,r,d\}\in MRD \qquad \text{(T4)}$$

$$U_{m,n,r,d} \le V_{m',r,d} \qquad \forall\{m,n,r,d\}\in MNRD,\; m'\in\{m,m'\}\in Q_{r,d} \qquad \text{(T5)}$$

Constraints (T6)-(T13) activated by *use_supply_ships*:

$$\sum_{\substack{p\in P_s \\ |r=r(p,d)}} Y_p \le V_{'ESCORT',r,d} \qquad \forall s\in SS, r\in R_{SSX}, d\in D \;|\; \text{not } close\_escort\_required \qquad \text{(T6)}$$

$$\sum_{\substack{p\in P_s \\ |r=r(p,d)}} Y_p \le \sum_{n\in N} U_{'CLOSE\_ESCORT',n,r,d} \qquad \forall r\in R_{SS}, d\in D \;|\; close\_escort\_required \qquad \text{(T7)}$$

$$X_{s,s',r,d} \le \sum_{p\in P_s|r=r(p,d)} Y_p \qquad \forall s\in SS, s'\in CS,\; r\in R_{SS}, d\in D \qquad \text{(T8)}$$

$$X_{s,s',r,d} \le \sum_{p\in P_{s'}|r(p,d)} Y_p \qquad \forall s\in SS, s'\in CS,\; r\in R_{SS}, d\in D \qquad \text{(T9)}$$

$$X_{s,s',r,d} \le \sum_{\substack{c\in C_{s'} \\ |'CAN\_HIT'\in M_c}} W_{s',c,r,d} \qquad \forall s\in SS, s'\in CS,\; r\in R_{SS}, d\in D \qquad \text{(T10)}$$

$$XFER_{s,s',d,i} \le \sum_{r\in R} cap_{s',i} X_{s,s',r,d} \qquad \forall s\in SS, s'\in CS,\; d\in D, i\in I \qquad \text{(T11)}$$

$$\sum_{s'\in CS} XFER_{s,s',d,i} \le \sum_{\substack{p\in P_s \\ |\exists\{d',d''\}\in D_p \\ \wedge d'\le d\le d''}} cap_{s,i} Y_p \qquad \forall s\in SS, d\in D, i\in I \qquad \text{(T12)}$$

$$\sum_{s'\in CS} XFER_{s,s',d,i} \le \sum_{d'\le d\le d''} LOAD_{s,d,i,d',d''} \qquad \forall s\in SS, d\in D, i\in I \qquad \{\text{T13}\}$$

$$\sum_{\substack{s \in SS, \\ d' \le d}} XFER_{s,s',d',i} - \sum_{\substack{c \in C_{s'}, \\ r \in R, \\ d' \le d}} use_{s',c,i} W_{s',c,r,d'}$$

$$+SLACK_{s',d,i} + V\_SAFE_{s',d,i} + V\_EXTR_{s',d,i}$$

$$= cap_{s',i} - init\_load_{s',i} + V\_OUT_{s',d,i} \qquad \forall s' \in CS, d \in D, i \in I \quad \text{(T14)}$$

$$U_{m,n,r,d} \in [0,1] \qquad \forall \{m,n,r,d\} \in MNRD$$

$$V_{m,r,d} \in \{0,1\} \qquad \forall \{m,r,d\} \in MRD$$

$$W_{s,c,d} \in \{0,1\} \qquad \forall s \in S, c \in C_s, d \in D$$

$$X_{s,s',r,d} \in [0,1] \qquad \forall s \in SS, s' \in CS, r \in R_{SS}, d \in D$$

$$Y_p \in \{0,1\} \qquad \forall p \in P$$

$$XFER_{s,s',d,i} \in [0, \min(cap_{s,i}, cap_{s',i})] \qquad \forall s \in SS, s' \in CS, d \in D, i \in I$$

$$LOAD_{s,d,i,d',d''} \in [0, cap_{s,i}] \qquad \forall s \in SS, d' \in D, d'' \in D \wedge d' \le d'', d \in D \wedge d' \le d \le d'', i \in I$$

$$SLACK_{s,d,i} \in [0, (1 - safe_i) cap_{s,i}] \qquad \forall s \in CS, d \in D, i \in I$$

$$V\_SAFE_{s,d,i} \in [0, (safe_i - extremis_i) cap_{s,i}] \qquad \forall s \in CS, d \in D, i \in I$$

$$V\_EXTR_{s,d,i} \in [0, extremis_i cap_{s,i}] \qquad \forall s \in CS, d \in D, i \in I$$

$$V\_OUT_{s,d,i} \ge 0 \qquad \forall s \in CS, d \in D, i \in I \quad \text{(T15)}$$

6. Discussion

The objective (T0) measures the weighted value of (partially) completed missions. Each (packing) constraint (T1) allows at most one employment schedule per ship. Each constraint (T2) permits a combatant to employ a

combined mission capability on a day only if an employment schedule has been chosen for that ship. Each constraint (T3) bounds the sum of the partial completion values of all instances of a given mission, in a given region on a given day, by the total amount of activity for that mission in the region. Each constraint (T4) allows a task to be considered fully completed in a region on a given day if there is at least one total units of activity for that mission in that region on that day. Each constraint (T5) allows activity in a region, mission, and day, only if a prerequisite mission in that region on that day has been fully accomplished. If close escort is not required, each constraint (T6) permits a supply ship to enter a region requiring escort only on a day for which the 'ESCORT' mission has been fully accomplished there; if the 'ESCORT' mission has been completed in a region, any number of supply ships may enter the region. If close escort is required, each constraint (T7) requires that the number of supply ships in a region on a day is limited by the level of accomplishment of the 'CLOSE_ESCORT' mission in that region that day; this means that there will be at least one combatant per escorted supply ship. Each constraint (T8) permits location of a supply ship for commodity transfer in a region of a selected employment schedule. Each constraint (T9) does this for a combatant, and each constraint (T10) allows collocation with a combatant only if the combatant employs the mission in the combined mission capable set. Each constraint (T11) limits transfer of a commodity between a supply ship and a combatant to a day when the ships are collocated in the same region. Each constraint (T12) limits the deliveries a shuttle ship can make during any epoch after a port visit to resupply. Each constraint (T13) limits deliveries from a supply ship during a deployment to its capacity. Each constraint (T14) accounts for a cumulative commodity used by a ship up to the end of a given day, and reckons any shortage below safety-, extremis-, or zero-stock levels (Note that any such shortage will be carried forward to later days until it is remedied by commodity transfer). Variable domains are defined by (T15).

D. MODIFICATIONS TO THE ORIGINAL NMP TO ENABLE LOGISTIC MODELING

In order to introduce logistic planning to NMP, we have modified certain aspects of NMP. For example, we have to add new missions such as consolidation (CONSOL), escort (ESCORT) and close escort (CLOSE_ESCORT), and transit (TRANSIT) to the concurrent mission capability set (CMC).

1. Concurrent Mission Capability Sets (CMC)

The CMC for a ship is based on the ship class and the design of the ship. For instance, cruisers or destroyers are more suited to conduct air defense (AD) and STRIKE mission than mine hunters. As discussed earlier, logistic ships are essential for maritime operations, and therefore very likely and opportune targets for opposing forces. The addition of two support missions to CMC's accounts for the necessary protection requirements of such units. In general, an escort mission is defined as a combatant ship accompanying a convoy or another military force to ensure appropriate protection for these units (JDP 1-02, 2001).

We define two distinct escort missions:

a. Escort

The general escort mission assures that a supply ship is protected while transiting through the regions of the AOO by the respective combat ships assigned to the region it currently transits. Protection duties are handed over to a unit in an adjacent region as soon as the supply ship enters that region. This relaxes force allocation planning, because it does not bind additional resources to accompany the supply ship at all times. This type of escort mission may only be suitable in an operating environment with a very low threat level. Although we describe the escort mission with the example of a supply ship, it may also be applied to other ships, for example, a CVN.

b. Close Escort

The close escort mission incorporates the same characteristics as the escort mission, but requires the planning tool to allocate resources (e.g., combat ships) to accompany each unit that needs protection at all times while transiting through the AOO. This mission is applicable during all threat levels, but certainly mandatory during the rise of hostilities and combat operations. In particular, close escort requires at least one combatant ship be assigned per supply ship in each region requiring such company and on each day requiring such.

c. Underway Replenishment

In order to account for the capabilities of supply ships we also add an UNREP mission to the CMC of all supply ship classes. An UNREP or replenishment at sea is defined as an operation necessary to transfer supply goods such as fuel, stores, ordnance, and personnel between ships at sea (JDP 1-02, 2001). This is a difference to the CLF planner, where we refer to underway replenishment as a consolidation (CONSOL). The difference is that a CONSOL describes an event where a CLF ships rendezvous with a BG to replenish the station ship or the entire BG. An UNREP specifically refers to two ships that execute a replenishment at sea alongside.

d. Transit

NMP now has a transit (TRANSIT) mission that accounts for ships transiting a region without conducting any other mission. Combatants in transit still consume commodities. A new region “rTransit” replaces any region on a transit route traversed in TRANSIT and unable to conduct any other mission at the same time.

2. Logistic Data

a. Consumption Factors

We insert logistic consumption factors to model daily use of commodities for a ship. These consumption factors are dependent on the crew size and the employment state of the ship. Similar to the CLF planner, we also use the aggregated four main commodity groups, DFM, JP5, STOR, and ORDN. The different employment states of a ship are those chosen by the optimization. Appendix A provides an overview of these factors.

b. Initial Load Outs and Maximum Capacities

A ship is characterized by its purpose, design, but also dimensions. Depending on these attributes, a ship has different capacities for each commodity. These capacities are incorporated in the data set. At the beginning of each planning epoch (e.g., 15 days) the planner needs to enter the current or initial commodity load out for a ship on the day she joins our operations.

c. Inventory Thresholds

Similar to the CLF planner, we introduce two inventory thresholds to NMP that serve as indicators for the model showing that a ship is short in supplies of one or more commodities. The first threshold, the safety level, is defined as the level of supply that is required to be on hand to permit continuous operations even if the normal rate of replenishment is interrupted or unpredictable fluctuation in supply occurs (JDP 1-02, 2001). The second threshold, the extremis level, situated below the safety level is defined as an inventory level that does not permit continuous operations without immediate support by a CLF unit. Both inventory threshold levels are associated with a penalty value that accumulates every day as long as the deficiency is not resolved and diminishes the overall value of the objective function.

3. Graphical User Interface

In addition to the functionalities and features already developed by Dugan and Silva, we add visualization in form of saw-tooth charts to support analysis on probable COA's from the logistic perspective. For instance, these charts disclose whether a COA is sustainable within the planning epoch and how future operations are affected. Furthermore, it assists in answering questions such as the minimum number of necessary CLF ships. Additionally, the planner can choose from three planning phases according to the phase planning model, which uses 6 phases (JDP3-0, 2006).

All data entries such as ships, consumption factors or combined mission capable sets in the graphical user interface can be edited by the planner to suit the operational requirements of a specific AOO. Furthermore, ship classes can be added to the model as long as required data for each new class is available.

Additionally, we insert a node that models the port Sasebo, Japan, where CLF ships can restock to their respective maximum capacity for each commodity for our scenario (we could add more such resupply ports). This is based on the assumption that we are operating in a confined AOO, and that most likely one or more Forward Logistic Sites or Advanced Logistic Support Sites are available somewhere, preferably in or near the AOO. This carries the implication that availability of ports to serve for logistic purposes has been negotiated prior to the beginning of operations, that critical supporting infrastructure such as a nearby airfield or cargo-handling facilities are available, and that all necessary commodities will be available to be transported to these locations.

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V. ANALYSIS AND CONCLUSION

A. SCENARIO

The two legacy theses on NMP, Dugan (2007) and Silva (2009), developed unclassified, face valid, but purely operational scenarios in the Korean Peninsula AOO. We use the scenario developed by Silva to show how incorporation of logistics impacts the scheduling of combat ships assigned to the area. For better illustration, the following paragraphs provide a quick overview about the scenario and the results obtained by Silva.

1. Missions

The original scenario includes eleven maritime mission types that are precisely described in Silva (2009). Appendix B provides a definition for each mission type that is taken from JDP 1-02 (2001). These mission types range from defensive missions such as air defense (AD), theater ballistic missile defense (TBMD), and intelligence (INTEL) to offensive missions, for instance, STRIKE, anti submarine warfare (ASW), surface warfare (SUW), and naval surface fire support (NSFS). They represent typical missions for maritime operations. Silva creates a portfolio of maritime missions scheduled over the extent of the planning horizon (Table 3).

Mission	Include	Type	Region	Start Day	End Day	Value	Requires		
m1	x	MIO	r1	1	4	9	AD		
m2	x	AD	r1	1	4	7			
m3	x	ASW	r1	1	4	8	AD	SUW	
m4	x	Intel	r1	1	4	7			
m5	x	TBMD	r2	1	15	20	AD		
m6	x	MIO	r3	1	4	5	AD		
m7	x	AD	r3	1	15	3			
m8	x	ASW	r3	1	4	4	AD		
m9	x	Intel	r3	1	15	3			
m10	x	MIO	r4	1	4	7	AD		
m11	x	AD	r4	1	15	5			
m12	x	ASW	r4	1	4	6	SUW		

Table 3 Missions

This excerpt of the mission table shows the primary mission type by region as well as the necessary prerequisite missions. Furthermore, it displays the mission values, which are the overall priority indicator, and the start day and end day for each mission. For example, mission m3 addresses ASW in region r1 from days 1-4, contributes mission value 7, but requiring that prerequisite missions AD and SUW be completed beforehand.

2. Area of Operation

The AOO is defined as the maritime region engulfing the Korean Peninsula. Silva introduces a network representation for the different operating regions in the AOO. It is understood that each node represents a region rather than a single position in the AOO. It can be thought of as an umbrella spanning from the node position depicted by its latitude and longitude with a varying radius to be defined by the operational planner. The arcs between adjacent nodes represent the shortest great circle distance in nautical miles between those nodes (Appendix E).

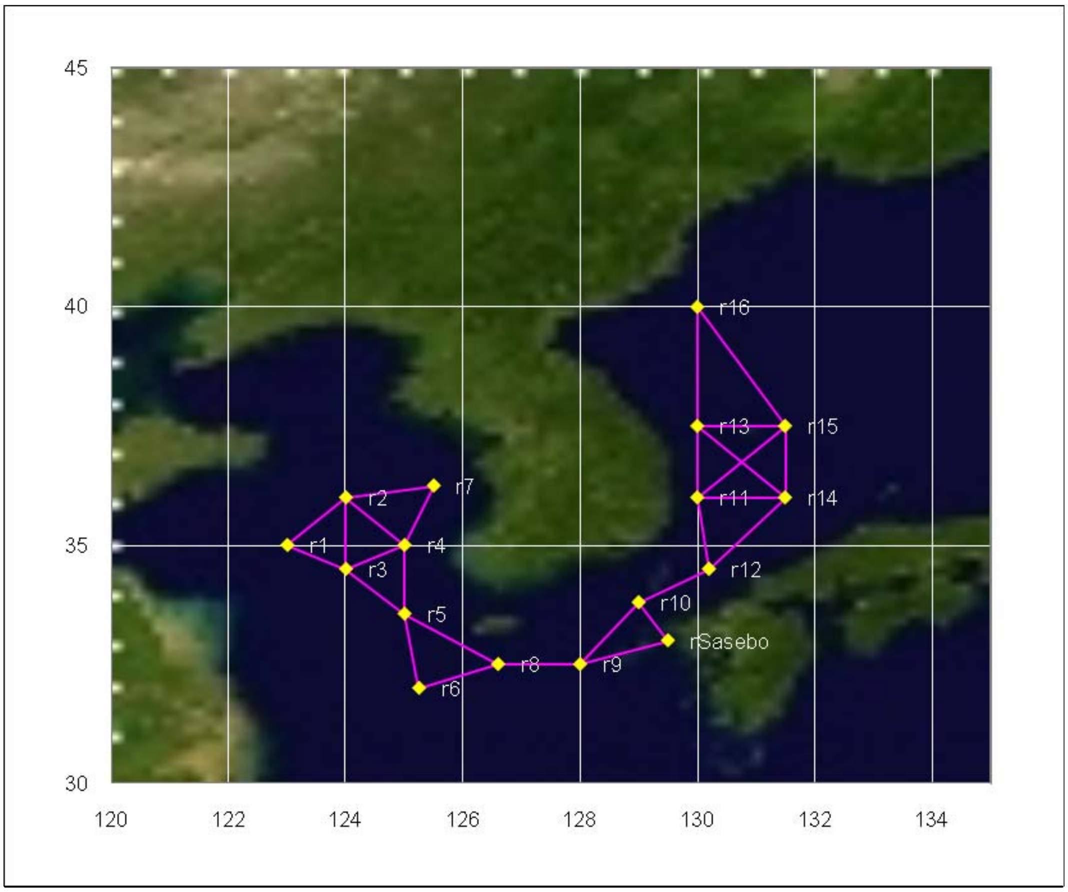

Figure 8 Area of Operations

This shows the confined AOO around the Korean Peninsula along with the network representation of the operating regions. Vertical and horizontal lines represent the grid for longitude and latitude. Nodes are represented as red (dark) points, while arcs are yellow (light) lines between those points. Figure from Excel Interface.

3. Forces

The ships allocated to the operation arrive over time into the AOO and the model assigns them to predetermined regions to conduct the required missions. The first ships to arrive are immediately available for tasking, while later arriving ships are tasked upon their estimated arrival. Specific arrival dates for ships and starting regions along with the necessary CMC's are entered into NMP by the planner. See Table 4.

Ship	Name	Avail	Class	Type	Start Day	Start Region	CMCs		
CG61	Monterey	x	CG	COMBAT	1	r2	C1	C5	C7
CG66	Hue City	x	CG	COMBAT	1	r13	C2	C5	C8
CG72	Vella Gulf	x	CG	COMBAT	4	r7	C3	C6	C9
CG58	Philippine Sea	x	CG	COMBAT	7	r10	C4	C5	C10
CG63	Cowpens		CG	COMBAT					
DDG53	John Paul Jones	x	DDG	COMBAT	1	r1	C11	C15	C17
DDG54	Curtis Wilbur	x	DDG	COMBAT	1	r4	C11	C15	C17
DDG86	Shoup	x	DDG	COMBAT	1	r9	C12	C15	C18
DDG90	Chaffee	x	DDG	COMBAT	1	r7	C12	C15	C18
DDG100	Kidd	x	DDG	COMBAT	4	r5	C13	C16	C19
DDG80	Roosevelt	x	DDG	COMBAT	4	r13	C11	C15	C17
DDG104	Sterett	x	DDG	COMBAT	4	r4	C11	C15	C17
DDG97	Halsey	x	DDG	COMBAT	7	r11	C11	C15	C17
FFG48	Vandegrift	x	FFG	COMBAT	4	r10	C21	C25	
FFG52	Carr	x	FFG	COMBAT	4	r11	C22	C25	
FFG47	Nicholas	x	FFG	COMBAT	7	r8	C23	C26	
SSN752	Pasadena	x	SSN	COMBAT	1	r12	C31	C37	
SSN718	Honolulu	x	SSN	COMBAT	6	r7	C34	C37	
SSN717	Olympia	x	SSN	COMBAT	1	r16	C33	C37	

Table 4 Force Composition

The force composition for the ongoing operation shows the sequential arrival of combat ships into the AOO. This shows that, for example, CG61, CG66, and DDG53 are available for tasking on day 1 of the operation, while CG72, DDG80, and FFG47 are available from day 7. We can also observe the starting region and candidate combined mission capability sets for each ship. The CMC's, denoted as CXX in this table, exhibit a ship's capability to conduct specific missions required in the operation. For example, C1 for CG 66 includes AD, SUW. (Figure from NMP Excel interface.)

4. Silva's Analysis Results

In the analysis of the baseline run Silva focuses on the accomplishment of prerequisite missions and high-priority missions. Silva finds that in some cases gaps or unaccomplished prerequisite missions lead to accomplishment gaps in primary missions. For example, mission m3, which an ASW mission from day 1-4

in region r1 adding the value of 8, requires AD and SUW to be accomplished. In this case, the primary mission remains unaccomplished, and thereby does not accrue any value. Additionally, because the prerequisite SUW is not a planner-scheduled mission for the first days in the time horizon, it does not contribute to the overall value achieved by the optimization. Furthermore, he also shows that NMP achieves more value in lower-priority local missions instead of dispatching a ship into another region with long off-station transit times. That results in long gaps even for the highest priority missions. For instance, a TBMD mission for the entire planning horizon in region r2 with value 20 remains unaccomplished, because the available assets do not suffice to generate enough AD, which is prerequisite for the TBMD mission in this region.

During the further course of the analysis, Silva alters mission assignments and maximum stall days (i.e., a limit on the number of days a combatant can stay in the same region) to improve the overall rate of completed missions. The number of maximum stall days forces a ship assigned to a specific region in the AOO to move on to another regions as soon as this planner-defined epoch is reached. In the following runs Silva adjusts the maximum stall day value until he extends it over the entire planning horizon. The results show that the optimization achieves the maximum value the longer ships are allowed to delay in a region. This ensures that the missions with the highest priorities get completely accomplished.

B. NMP WITH LOGISTICS

We will use Silva’s final scenario as the starting point for the analysis of the enhanced features added to NMP. The baseline run examines whether the optimized operational plan is valid without logistic support. In subsequent runs, we enable logistics to evaluate the enhanced features of NMP. We include a small force of CLF ships to see whether the operational plan found by the optimization is sustainable with CLF support.

Preliminary solutions during the test phase of NMP with logistics show that for this particular scenario DFM is the most crucial commodity. Therefore, we concentrate on the DFM inventory levels. We use the logistic consumption factors for phase 2 (Figure 1). Additionally, we make minor changes to the CMC matrix (Appendix C) because the legacy CMC sets restrict combatants, which causes other ships not to get assigned to deployment plans. We set the penalties for violating the safety level threshold to 0.00001 mission accomplishment units per barrel per day (DFM, JP5), and 0.001 units per short ton per day (STOR, ORDN), and subtract any such penalty from the mission value. The penalty for violating the extremis value is 0.5 for all commodities and 1, if a ship runs out of any commodity.

1. Initial Run

For this run we use the settings from Silva's fourth run as our initial set up (Silva, 2009, p.28 ff), and turn on the new logistics feature of NMP. The setup includes 15 surface combatants and three nuclear submarines. We consider 80 required missions spread all over the AOO, with 57 requiring accomplishment of one or more prerequisite missions. Table 3 shows an excerpt of the required missions. The initial run generates a small mixed integer program with that 15000 variables of which about 12000 are binary, and about 3000 constraints. This instance solved in under 1 minute because we do not impose any logistic restriction to the model.

We observe that the objective value is 3379.50; because the ongoing consumption of commodities without logistic support imposes penalties for each day any ship drops below the safety level threshold, or below extremis level, or runs out of a commodity. The first combatant depletes its entire DFM inventory by day 9, followed by other ships. This is illustrated in Figure 9, and shows that the operational plan found by the optimization is not sustainable without the support of CLF ships. We account for these inventory alarms by penalizing our objective function, rather than declaring outright infeasibility, reasoning that it is

better to exhibit why this happens. The penalized mission value objective is degraded to 1871.50 by these inventory violations.

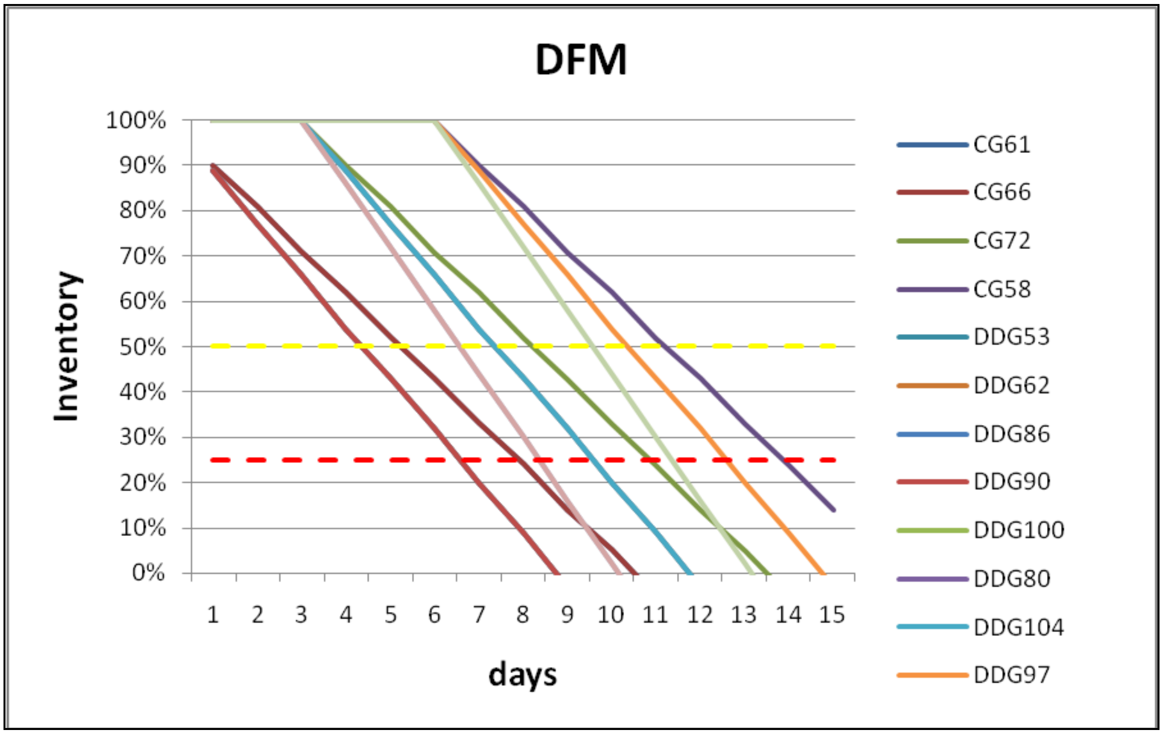

Figure 9 Initial Run Saw-tooth Diagram
This saw-tooth diagram shows the daily consumption of DFM for each individual ship in a different color. We clearly observe, that 92% of the ships run out of DFM over the planning horizon, which indicates, that the operational plan is infeasible without logistic support. Some series overlay one another, and thus not all series are being displayed properly.

2. Second Run – Include Logistic Support

For this run, we include a small CLF force to support the surface combatants. The CLF force is composed of 3 fleet replenishment oilers (T-AO), 1 fast combat supply ship (T-AOE), 3 combat stores ships (T-AFS), and 1 Modular dry cargo and ammunition ship (T-AKE). This represents a balanced mix of CLF ships enabling underway replenishment with all necessary commodities. The CLF ships are spread out over the AOO, accounting for regions that have ships assigned. We let the optimization determine the optimal deployment schedule for combatants and CLF ships.

We observe that the objective function mission value increases from 1871.50 to 2259.81. This is a logical result from the utilization of the CLF ships, because now the optimization regularly schedules UNREP's to supply the combatants. Figure 10 shows the saw-tooth diagram for DFM that clearly illustrates the use of the CLF ships. Appendix D shows and excerpt of the generated deployment plan for a CLF ship.

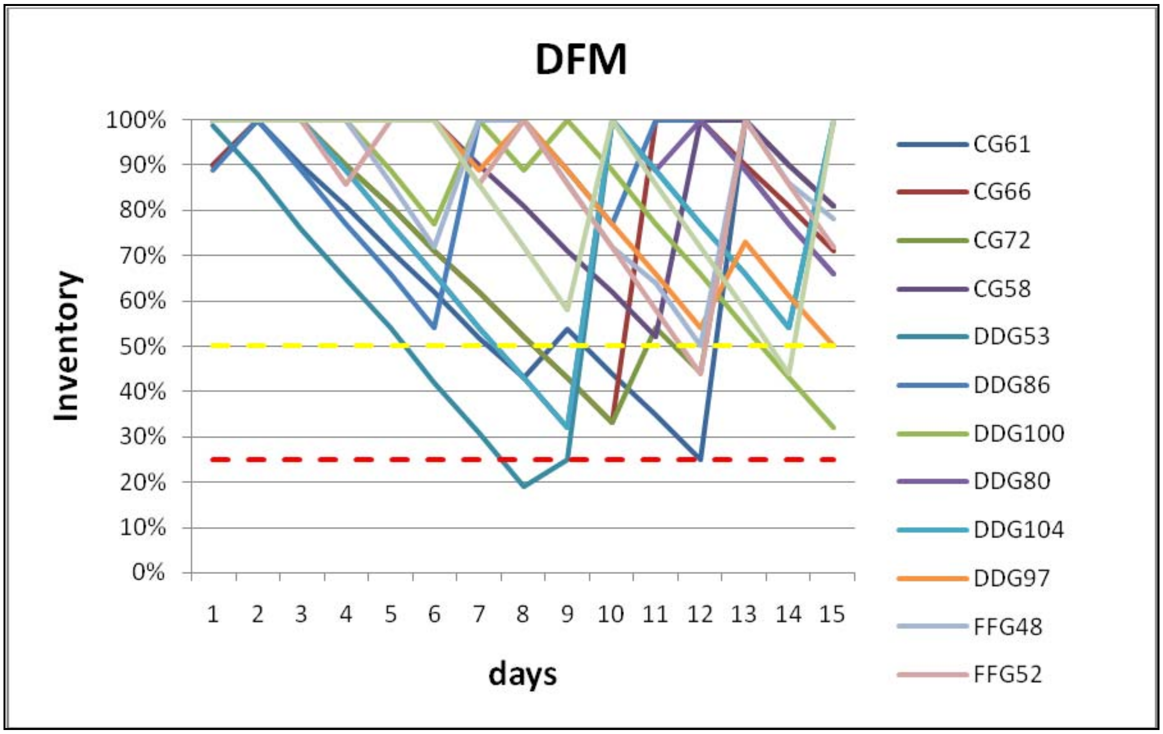

Figure 10 Second Run Saw-tooth Diagram

This shows the saw-tooth diagram of the daily consumption of DFM for each individual ship in a different color and activated CLF ships. We observe that some ships violate the safety level and one ship violates extremis level for one day. This shows the operational plan is sustainable with the activation of supply ships.

3. Third Run – "Delivery Boy" Approach

In this run, we examine the "delivery boy" approach. This features a given, fixed operational plan including the employment of combatants and required missions. Then we determine the optimal deployment schedule for CLF ships to support these fixed combatant employments. We first use the optimization

without the logistic feature to find an optimized operational plan yielding the highest mission accomplishment objective function value. Then, we fix these combatant deployment plans, turn on the CLF feature, and use the model to determine the optimal deployment plans for the CLF ships to support the given operational plan.

The mission accomplishment objective function value for this scenario is 3271.35. The solve time is about 3 hours, which is acceptable in the planning phase of an operation, and can likely be improved by model refinements. The generated saw-tooth diagram (Figure 11) illustrates that ships drop below the safety level threshold, but do not fall below extremis level.

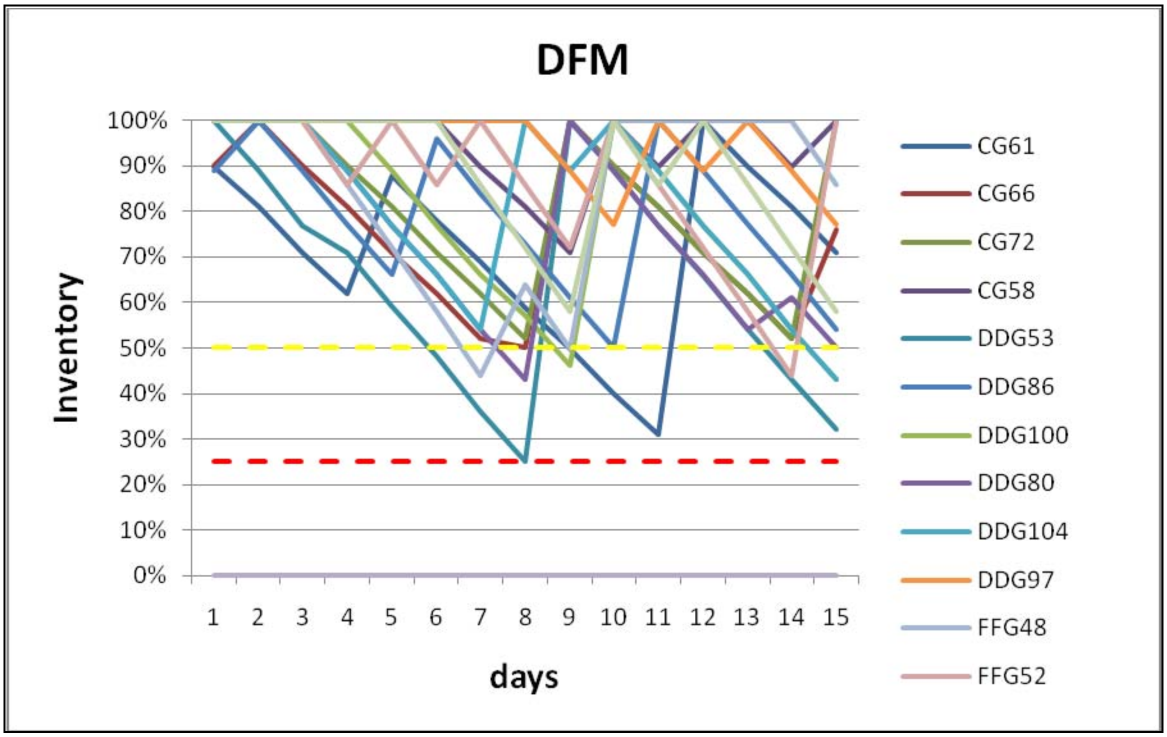

Figure 11 Third Run Saw-tooth Diagram for "Delivery Boy" CLF Service
This saw-tooth diagram shows the consumption of DFM for each ship in a different color. The "delivery boy" approach yields suitable deployment schedules for CLF ships ensuring sufficient support for combat ships.

4. Fourth Run – "Gas Station" Approach

In the final run, we examine the "Gas Station" approach, where we fix CLF ships in prepositioned locations of the AOO. We manually create one deployment schedule for each CLF ship fixing her in one region for the entire planning horizon (we could also fix a CLF employment schedule to move region-to-region as we please). With CLF support activated, we then find deployment schedules for the combatants.

The mission accomplishment objective value decreases to 3061.17, because now the combat ships need to seek a prepositioned CLF ship in order to get replenished. For example, DDG 53 cannot transit into an area where a CLF ship is prepositioned until day 8. This ship drops very low in DFM inventory, but gets resupplied in time. However, this shows that the optimized operational plan or the manual prepositioning of CLF ships may have to be adjusted. The following saw-tooth diagram (Figure 12) shows decreased replenishment opportunities due to the prepositioning of CLF ships, resulting in more ships dropping below the inventory threshold levels.

Regarding the inventory levels of the CLF ships, we observe that given a planning horizon of 15 days the commodity inventory is sufficient to replenish all combatants.

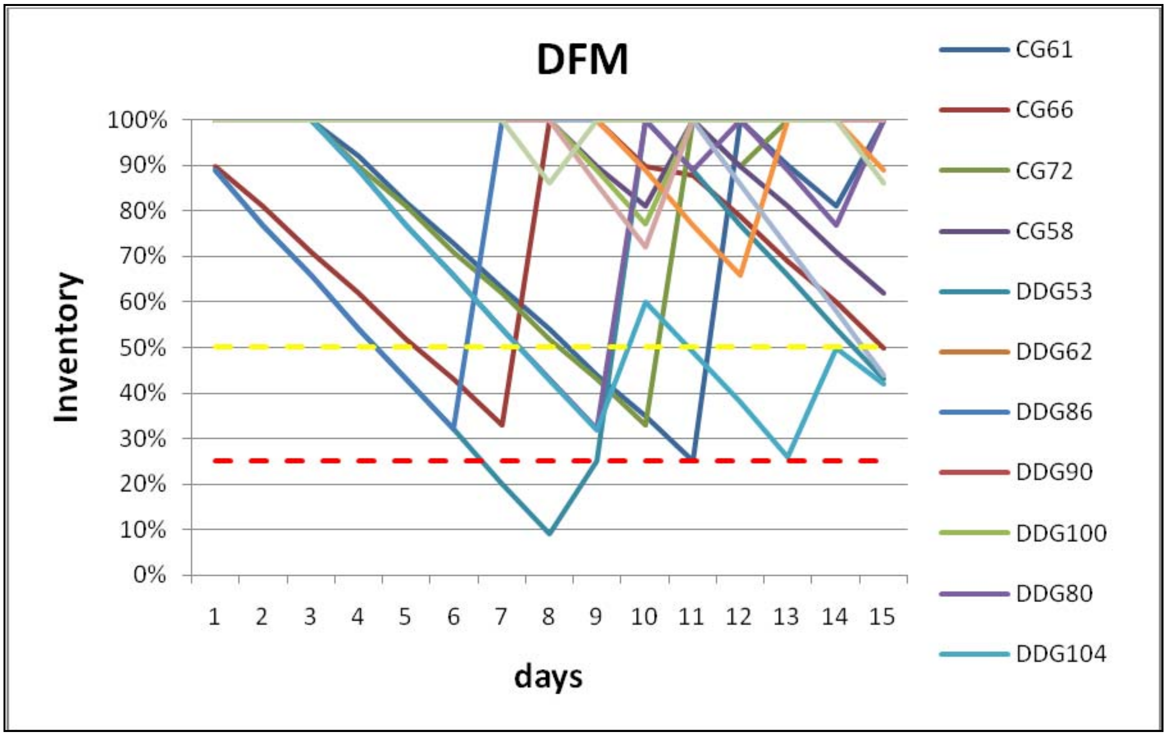

Figure 12 Fourth Run Saw-tooth Diagram for "Gas Station" CLF Service. This saw-tooth diagram shows DFM inventory levels for each combat ship in a different color. With fixed, prepositioned CLF ships, we observe that multiple combatants drop below safety stock level and one ship drops below extremis level. Nevertheless, the operational plan found by the optimization is sustainable.

5. Additional Insights

When activated, the constraints enforcing the requirements of either ESCORT or CLOSE_ESCORT missions for shuttle ships impose such a significant restriction on the model that it significantly increases the runtime, and yields much lower quality solutions. We have not been able to solve these more restrictive models to optimality for any instance. However, when we review the results from prior runs of the model that do not require ESCORT for supply ships, we find that the solutions for many of these instances can satisfy these requirements, in the sense that every supply ship on every day of its optimal schedule is collocated with a combatant ship using CMCs that contain the ESCORT mission.

CLOSE_ESCORT turns out to be infeasible for the combatants and missions presented by Silva, and the CLF ships available. This is not a criticism of Silva, but rather an observation that operational plans will need polishing to protect CLF ships when CLOSE_ESCORT is required. That is, operational plans will have to be relaxed, or rescheduled, to render employments that can be supported by CLF ships.

C. CONCLUSION

1. Summary

Maritime Commanders and their planning staffs dedicate a great amount of time planning maritime operations prior to force deployment. Thereby, it is necessary to address all important factors in the planning process, especially logistic requirements necessary to sustain operations for the anticipated planning horizon. We discuss two operational level decision aids to support maritime commanders. These decision aids enable evaluation of different courses of action in a short amount of time. Moreover, they allow for different planning approaches. While the CLF planner requires existing operational plans imported in the form of exogenous BG navigational tracks to find optimized employment schedules only for CLF ships, NMP addresses operational and logistic planning, and yields optimized employment schedules not only for CLF ships, but also for combatants. Furthermore, it may also evaluate fixed strategies for either combatants or supply ships. CLF solve times are about 5-10 minutes for the scenarios displayed, while NMP-CLF solve times can be much longer when we add CLF restrictions. These times vary with the complexity of the scenario, but are sufficient for timely analysis of multiple courses of action.

2. Future Research

a. Heuristic

The NMP as well as the CLF planner use the general algebraic modeling language (GAMS) and the commercial solving algorithm CPLEX to

evaluate the optimization model and produce deployment schedules. GAMS is not available on standard Navy Marine Corps Internet (NMCI) computers, which restricts the use of the tool to specially-configured stand-alone personal computers. This obstructs the integration of these planners into planning cells such as Maritime Headquarters with maritime operation centers, and therefore the availability of these tools to planners. Furthermore, some of the solvers used, such as CPLEX, are proprietary with expensive individual user licenses (GAMS Development Corporation, 2009). Therefore, the development of a heuristic algorithm to solve the optimization model will provide availability for NMCI computers and improve the process of integrating these decision aids into the existing information technology infrastructure.

b. Expanding the Horizon by Increasing Versatility

The current release versions of NMP and CLF are populated with data for USN units only, and do not contain the necessary input for coalition forces such as NATO navies or coalition partners of opportunity. Because the consumption data for fuel, diesel fuel marine (DFM) as well as aviation fuel (JP5), stores, and ordnance are not easy to obtain through open sources, consumption data may be estimated depending on the ship’s characteristics such as size, propulsion system, warfare systems, etc., using USN combatants as analogies when applying the logistic planning factor equations to units from coalition navies (Miller, 1992, p. 138). Valuable information about characteristics can be obtained from unclassified publications such as Jane’s Fighting Ships (Jane's Information Group, 2009). Including coalition forces improves the versatility of both NMP and CLF, and opens opportunities to use the decision aids for a multinational coalition. This will contribute to the overall efficiency and effectiveness of maritime mission planning, and may also have a positive impact from an economic standpoint.

c. Include Land Component into the Planning Tool

Today's battlefield does not necessarily end at the shore of a country. In the joint world, many combatant commanders often are responsible for multiple warfare areas with multiple component commanders supporting the overall planning process. A decision aid incorporating operational and logistic planning function on the operational level may assist streamlining the process. Therefore, it may be beneficial to include the land component into the planning tool by developing a network presentation of the operation area ashore, where nodes represent operating regions, and arcs represent the shortest distance between adjacent regions. Certain nodes may be characterized as principle supply points allowing application of a network flow algorithm. This feature may also include some representation of Time-phased-Force and Deployment Data (TPFDD).

d. Accommodate Delay of Dependent Missions

For some planning scenarios, missions (or sets of missions) must be completed before other missions (or sets of missions) can be commenced. For lack of available combatants, it may be necessary to slip the entire operational plan to accommodate this. A slight generalization of the dependencies among missions can reflect that there are time dependencies that can be signaled by "phase completion" mission events. Completion of such an event may have no objective value, per se, but would be prerequisite to commencing missions in the subsequent phase. Each mission completion can either be expressed as "durable" or "temporary." A temporary mission must be completed every day during a phase of missions, while a durable one need be completed only once during the phase. These relationships can all be expressed by prerequisite dependencies in the data.

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APPENDIX A. CONSUMPTION FACTORS

The following table shows the logistic consumption factors for each modeled ship type. The factors are displayed for each of the four main commodities, and summarized by the respective operational planning phase.

Consumption factors					
Mission Phase	Ship type	DFM	JP5	STOR	ORDN
Phase 2	CVN	0	3000	53	0
	CG	1429	5	2	0
	DDG	1200	5	2	0
	FFG	600	5	1	0
	LCS	360	0	0.25	0
	SSN	0	0	1.5	0
	SSGN	0	0	2	0
	MCM	250	0	0.5	0
	TAOE	2570	10	1	0
	TAO	960	10	1	0
	TAKE	960	10	1	0
	TAFS	960	10	1	0
Phase 3	CVN	0	5000	53	150
	CG	757	39	2	5
	DDG	646	34	2	3
	FFG	304	39	1	1
	LCS	180	1	0.25	2
	SSN	0	0	1.5	5
	SSGN	0	0	2	5
	MCM	125	0	0.5	0
	TAOE	960	10	1	0
	TAO	960	10	1	0
	TAKE	960	10	1	0
	TAFS	960	10	1	0
Phase 4	CVN	0	4000	53	100
	CG	757	19	2	3
	DDG	646	19	2	2
	FFG	304	19	1	0.75
	LCS	180	0.5	0.25	1
	SSN	0	0	1.5	2
	SSGN	0	0	2	2
	MCM	125	0	0.5	0
	TAOE	960	10	1	0
	TAO	960	10	1	0
	TAKE	960	10	1	0
	TAFS	960	10	1	0

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APPENDIX B. COMBAT MISSIONS

The following table provides a list of maritime missions used in the NMP model that are common to maritime operations.

Acronym	Long Title	Description
AD	Air Defense	Defensive operations designed to engage enemy aircraft or missiles.
TBMD	Theatre Ballistic Missile Defense	Operations against enemy missiles
ASW	Anti Submarine Warfare	Operations to deny the enemy the effective use of its submarines.
SUW	Surface Warfare	Operations conducted to destroy or neutralize enemy surface ships including merchants.
STRIKE	Strike	Offensive operations to destroy enemy infrastructure or a capability.
NSFS	Naval Surface Fire Support	Operations using naval gun and missile systems to support friendly units.
MIO	Maritime Interdiction Operation	Operations to monitor, query, and board merchant traffic in international waters.
MCM	Mine Countermeasures	Operations conducted to prevent danger and reduce damage originated from mines.
MINE	Mine Warfare	Strategic, operational, and tactical use of mines in order to decrease the enemy’s operational versatility.
INTEL	Intelligence Collection	Collection of information about foreign nations or hostile forces in areas of interest.
SUBINTEL	Submarine Intelligence Collection	Intelligence collection in a covert manner that has to be conducted by a submarine.
UNREP	Underway Replenishment	Operations to distribute commodities, or personnel between two or multiple ships at sea.
ESCORT	Escort	Operations to ensure protection for high value units within a theater of operations with low risk.
CLOSE_ESCORT	Close Escort	Operations to ensure protection for high value units within a theater of operations with high risk.

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APPENDIX C. COMBINED MISSION CAPABILITY SET MATRIX

The CMC matrix describes concurrent mission capabilities by ship type. The table shows the original CMC table embedded in the NMP graphical user interface. A definition of each mission included in each of the CMC and displayed in the first row of the following table can be found in Appendix B.

		Mission															
Ship Class	CMC	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	UNREP	SubIntel	CAN_HIT	ESCORT	CLOSE_ESCORT	TRANSIT
CVN	C1	1	0	1	1	1	0	0	0	0	0.5	0	0	0	0	0	0
	C2	1	0	1	0.5	1	0	0	0	0	0.5	0	0	1	0	0	0
	C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
CG	C4	1	0	1	1	1	1	0	0	0	1	0	0	1	1	1	0
	C5	1	0	0.5	1	1	0.75	0	0	0	1	0	0	1	1	1	0
	C6	0	0	1	0.5	1	0.5	0	0	0	1	0	0	1	0	0	0
	C7	1	0	0	1	1	1	0	0	0	1	0	0	1	1	1	0
	C8	0	0	0	1	1	0	1	0	0	1	0	0	1	0	0	0
	C9	1	0	0	0.5	1	0	1	0	0	1	0	0	1	1	1	0
	C10	0	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0
	C11	0	1	0.5	1	1	0.75	0	0	0	1	0	0	0	0	0	0
	C12	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	C13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
DDG	C14	0	0	1	1	1	1	0	0	0	1	0	0	1	0	0	0
	C15	1	0	0.5	1	1	0	0	0	0	1	0	0	1	1	1	0
	C16	0	0	1	0.5	1	0.5	0	0	0	1	0	0	1	0	0	0
	C17	1	0	0	1	1	1	0	0	0	1	0	0	1	1	1	0
	C18	1	0	0	1	1	0	1	0	0	1	0	0	1	1	1	0
	C19	0	0	0	0.5	1	0	1	0	0	1	0	0	1	0	0	0
	C20	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0
	C21	0	1	0.5	1	1	0.75	0	0	0	1	0	0	0	0	0	0
	C22	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	C23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
FFG	C24	1	0	1	1	0	0	0	0	0	0	0	0	1	1	1	0
	C25	0	0	0.5	1	0	0	0	0	0	0	0	0	1	0	0	0
	C26	0	0	1	0.5	0	0	0	0	0	0	0	0	1	0	0	0
	C27	0	0	0.67	0.67	0	0	0	0	0	0	0	0	1	0	0	0
	C28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	C29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
LCS	C30	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	C31	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
	C32	0	0	0	0.5	0	0	1	0	0	0	0	0	0	0	0	0
	C33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SSN	C34	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	C35	0	0	1	0.5	0	0	0	0	0	0	0	0	0	0	0	0
	C36	0	0	0.5	1	0	0	0	0	0	0	0	0	0	0	0	0
	C37	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	C38	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	C39	0	0	0	0	0	0	0	0	1	0	0	0.5	0	0	0	0
	C40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SSGN	C41	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	C42	0	0	0	0	0	0	0	0	1	0	0	0.5	0	0	0	0
	C43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
MCM	C44	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
	C45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TAOE	C46	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
TAO	C47	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
TAKE	C48	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
TAFS	C49	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

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APPENDIX D. CLF SHIP EMPLOYMENT PLAN

The following table shows an excerpt of the generated CLF employment plan for the “delivery boy” approach indicating on which day and in which region a CLF ship replenishes a combatant. Additionally, it shows the commodities, the amount transferred, and the inventory level of a CLF ship.

TAOE6			**INVENTORY**			
Day	**Region**	**UNREP**	**DFM**	**JP5**	**STOR**	**ORDN**
d1	r5		62400	93600	952	2016
d2	r6		cargo available			
d3	r8		cargo available			
d4	r5	DDG100	cargo available			
			1200	0	2	0
d5	r6		cargo available			
d6	r8		cargo available			
d7	r5	DDG100	cargo available			
			3600	0	0	0
d8	r6		cargo available			
d9	r8		cargo available			
d10	r5		cargo available			
		DDG53	9088.5	5	2	0
		DDG104	8400	35	14	0
		FFG47	2400	10	2	0
d11	r3		cargo available			
d12	r1		cargo available			
d13	r2		cargo available			
		CG61	12703	20	8	0
		CG72	9801.5	10	4	0
d14	r3	cargo available				
d15	r5		cargo available			
		DDG53	6000	0	0	0
		DDG104	6000	10	0	0
		FFG47	3000	0	2	0
DELIVERY STATISTICS:			**62193**	**90**	**34**	**0**

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APPENDIX E. DISTANCE TABLE

The following table shows the distances between the regions in the AOO in nautical miles. They represent the shortest great circle distance calculated with visual basic subroutines embedded in the graphical user interface.

Region	LON	LAT
r1	123	35
r2	124	36
r3	124	34.5
r4	125	35
r5	125	33.56
r6	125.25	32
r7	125.5	36.25
r8	126.6	32.5
r9	128	32.5
r10	129	33.8
r11	130	36
r12	130.2	34.5
r13	130	37.5
r14	131.5	36
r15	131.5	37.5
r16	130	40
rSasebo	129.5	33

Arcs		Length(nm)
r1	r2	77.39280636
r1	r3	57.72718773
r2	r3	90.02854213
r2	r4	77.39280636
r2	r7	74.25004258
r3	r4	57.72718773
r3	r5	75.21262615
r4	r7	78.88936606
r4	r5	86.42740045
r5	r6	94.47561702
r5	r8	102.6105451
r6	r8	74.80783582
r8	r9	70.86683985
r9	r10	92.80463462
r10	r12	72.92193612
r11	r12	90.56058562
r11	r13	90.02854213
r11	r14	72.83390191
r11	r15	115.3594323
r12	r14	110.2928619
r13	r14	115.3594323
r13	r15	71.42368869
r14	r15	90.02854213
r13	r16	150.0475702
r15	r16	165.6549877
rSasebo	r9	81.44652121
rSasebo	r10	54.1581819

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